Water resources in Saudi Arabia with particular reference to Tihama Asir province

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Water Resources in Saudi Arabia with Particular Reference to Tihama Asir Province

Thesis Submitted in partial fulfillment of The Degree of Doctor of Philosophy

By

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IN THE NAME OF ALLAH

THE MOST BENEFICENT, THE MOST MERCIFUL

Abstract

Although Saudi Arabia has made great progress in almost all aspects of development, the availability of water has remained problematic. It is, therefore, important to study water resources, and also the increasing water demands in Saudi Arabia in general, and in Tihama Asir in particular.

Climate is influenced to a limited extent by the relatively high altitude of the mountains, especially where rainfall is concerned, and an annual average between 30mm and 300mm is recorded. The rate of evaporation, however, is very high, because of the cloudless sky and high temperatures.

Runoff occurs only after torrential and monsoon rain, when the wadis collect flood waters from their many tributaries. Two hundred dams have been built in recent years in an attempt to increase underground water recharge, and to provide potable water in sufficient quantity and quality, and to provide for irrigation.

The ground water resources, including the shallow aquifers of wadis and the deep aquifers, could be of greater benefit with the modification of their current use.

A large number of desalination plants have been constructed along the Red Sea and the Arabian Gulf to meet the increasing water demands of Saudi Arabia's increasing population. The utilization of treated sewage effluent should be increased to stop the threat of ground water contamination and to reduce the pressure exerted on available resources.

Results indicate that modern irrigation methods reach high levels of average field irrigation efficiency, and traditional practices show the highest average levels of energetics performance.

Based on water resources and water budget analysis the following recommendations are suggested to the Ministry of Agriculture and Water with regard to water uses in Saudi Arabia and Tihama Asir in particular.

- Modernize traditional and intermediate irrigation methods on as many acres as feasible.

- Introduce small green-houses on as many private farms as possible.

- Develop water resources extension service programmes and training programmes that address fundamental aspects of improving domestic water use, and alternatives to natural and artificial supplies.

The developed database can be used as an information source to support future water resource-oriented decision making.

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Declaration

The contents of this thesis are the work of the sole author alone, and have not previously been submitted at this or any other university.

Copyright

Dedication

To the soul of my father

and those of my family

and my friends

who have passed away.

Chapter One

Introduction

Almighty God says in the holy Koran:

*"And we send the fecundating winds,
Then cause the rain to descend From
the sky, therewith providing you with
water (in abundance), Though we are not
the guardian of its stores."*

Al-Hujrat - 22

He also said:

*"For among rock, there are some from
which rivers gush forth; others there
are which when split asunder send
forth water."*

Al-Baqara - 74

1.1 Introduction

Saudi Arabia as a geographical region is an arid place: low rainfall; high daytime temperatures mean that (potential) evaporation rates are very high; surface water is unusual, and tends to be confined to oases; there are few surface water flows, and these are usually in the form of floods; there is little natural soil water available to vegetation, and so the indigenous flora resembles that of other arid places in the world; many of the soil types can be classified with soils associated with arid regions.

Saudi Arabia as a political entity has access to considerable amounts of water from rainfall; groundwater; fossil water; artificial sources of water, such as desalination and waste water treatment; and imported water. Despite these substantial resources, Saudi Arabia has a major problem in that future demand for water is projected to outstrip supply, and present demand is already in excess of rates of replenishment. Water resource development policy has largely focused on facilitating the availability of water from existing renewable sources (e.g. sinking more and deeper boreholes into aquifers which already support many wells); accessing non-renewable sources, such as fossil water and imported water; and using its considerable financial wealth to develop and exploit desalination technology. By these means, Saudi Arabia is not currently short of water for domestic, industrial or agricultural uses, given the current position of economic, industrial and agricultural development. However, the aspirations of the Saudi government and people lie beyond the present state of development. If current water demand is in excess of rates of replenishment, continued economic, industrial and agricultural development can only exacerbate the problems. Water links the natural environment with politics.

This thesis examines the nature of the problems of water supply and demand, and the impact they are likely to have upon present and future water resource development (MAW and El-Khatib, 1980). Whilst the arid regions of the world are widely heterogenous (Agnew and Anderson, 1992), there are some globally-applicable lessons to be learned from the Saudi experience.

Attempts made to develop water resources involve modification of the hydrological cycle. Such interference is unlikely to continue without an impact on the region's natural ecosystems. Given the complexity of arid zone ecosystems, and the superficiality of current understanding, the effects of water resource development are poorly understood. Water resource development in Saudi Arabia is being planned with little consideration for ecological implications.

Tihama Asir is the one region of Saudi Arabi blessed with rainfall which can, to a reasonable extent, be depended on for shallow aquifer recharge. To the south west of the country, and therefore far from the oil-related industrial development of the north east, and the urban commercial development of the Riyadh (centre) and Jeddah, Makkah and Taif (west), it is a region which has, until recently, experienced little economic development. For Saudi Arabia, Tihama Asir may be a valuable asset in the exploitation of indigenous water resources. What will be the social and environmental impacts as Tihama Asir is jerked onto the runway of modern economic development? This question is predicated on the recognition that societies have developed and adapted to work within the environmental framework in which they are located. Arid realm societes worldwide are structured for survival within the arid realm. Economic development has not only a direct impact on a society in changing the nature of the social relationships, but also as a result of environmental effects, in particular the development of water resources, further moulds the shape of the society. Tihama Asir has many scattered villages, each tapping shallow aquifers. Too great a population concentration leads to an unsustainable demand on water resources. Economic development has always entailed enhanced access to water resources. In the case of Tihama Asir, this is leading to the exhaustion of the shallow aquifers. The economic need to optimise the production and use of resources tends to precipitate population relocation to the sites of resource production and use, and therefore the rural to urban drift, which characterises much of Saudi Arabia. In order to have access to water, therefore, the population of Tihama Asir will have to change from the sustainable arid realm social structure of scattered villages, to the technologically-dependent social structure of economically (over-)developed societies worldwide.

1.2 Water Resources in the Arid Realm

1.2.1 The World View

Arid and semi-arid areas, which amount to one-third of the land area of the earth's surface, suffer from a deficiency of natural fresh water resources.

Access to fresh water has always been a decisive factor in maintaining human habitation: the location of the earliest human habitation was determined by proximity to sufficient fresh water, such as from rivers, lakes and springs.

The historic relationship between man and water has, in modern times, become increasingly complex. Current water demand and anticipated future needs present considerable uncertainty. Population growth, urban and industrial expansion, and the demand for food are the main causes for this complexity.

By the end of the twentieth century, the world population is predicted to be twice what it was in 1968, and it will continue to increase at that rate for many years to come. From 3.3 billion in 1968, it expected to be over 7 billion in the year 2000, and will probably reach 20 billion by the middle of the twenty-first century (Al-Matari, 1984 and George, Pierre - translated by Fakeladeh Samouhi, 1985).

The problem of water supply is made more extreme by urbanisation. The worldwide flow of people from rural to urban areas has accelerated in recent years.

Water consumption per capita varies widely across socio-economic groups. Moreover, industrialisation, which accounts for substantial use of available water and often contributes to the reduction of existing water supplies through contamination, tends to concentrate in urban areas as well.

Global demand for food also is increasing, especially in developing countries where food production lags behind population growth. Irrigated land in the developing world amounts to about 20% of the total arable land, but expanding agricultural areas is dependent upon finding new water resources.

Water resources in the Gulf Countries have been studied in detail. Water supplies are clear, regardless of the giant strides taken by countries in the area to develop the new sources of desalination and waste water recycling. Political tension over water resources between Gulf countries is much lower than between other Middle Eastern countries.

It has been disclosed that Bahrain is extracting groundwater in excess of 180 mcm/annum from the Dammam aquifer when the recommended safe yield should have been around 83-90 mcm/annum. In Qatar, the groundwater deficit reached around 84.6 mcm/annum while most drinking water is currently being supplied at a rate of 62 mcm/annum from desalination plants. Qatar, like the other countries in the region, has no contingency for emergency measures in case of total breakdown of the desalination plant in Doha. Indeed, the only option is to revive shelved plans for an additional desalination plant to meet such an emergency.

The Gulf countries have turned to desalination to solve their drinking water shortage. The domestic needs to the cities in all countries were being met from desalination plants, mostly attached to power generation stations (Uqba, 1991). The 1984 projection for the late 1980s of annual output from desalination plants in the Gulf countries totalled around 1242 mcm, of which 42% was produced in Saudi Arabia alone (530 mcm) (The Fourth Development Plan and Saline Water Conversion Corporation (SWCC), 1984).

In Kuwait, much effort has been made to reduce drinking water shortages. In the desert areas, people traditionally depended on shallow wells and seasonal rainstorms for their water supply. In 1925, the limited quantity forced them to bring water by small sailing barges from Shatt al Arab in southern Iraq, a distance of about 120 km. Due to inadequate water conveyance methods, both quantity and quality were poor and the supply was irregular. To improve these conditions, the government of Kuwait constructed its first desalination plant in 1950. Currently, the country gets most of its water supply from the sea (Al-Rasheed, 1967).

The problem of water resources in the Arabian Gulf countries is embodied in the paradox of continued ambitions in extensive farming despite steady depletion groundwater resources. The present situation is clearly expressed in four related economic aspects: water, agriculture, population and food imports. Given the ratio of groundwater abstraction for domestic use to that for agricultural use as 1:19 (5% for domestic use and 95% for agricultural use, of total groundwater volume extracted, Uqba, 1991), a ratio maintained since the Trucial States Survey of 1966-69, then the population, most of whom are urban dwellers, can provide little explanation for the big surge in groundwater extraction. Most of the needs of the large towns at present are being provided by desalinated water. For example, the total daily output from seawater desalination in Abu Dhabi throughout 1989 was $442.39m^3/d$, of which only $154.57m^3/d$ (35% of the total) were actually consumed by the population of the town. Of the total daily production, 18% was pumped to Al Ain (74.62-79.95 m^3/d), while the rest (47%) was lost between the irrigation of municipal reserves, 'unaccounted for' leakages and clandestine connections (Uqba, 1991). Groundwater reserves are already in the stage of over-development. Extraction over the past decade and a half has been, in effect, the mining of the system. Brackish water aquifers are also over-developed, and fresh groundwater in Quaternary deposits is almost depleted. Pump intake levels in most parts of the country have sunk from an average depth of 60-100m, 10 years ago, to 300-1500m.

Only the desalinated water production of the main coastal towns and the potable groundwater output of the towns of Dubai, Sharjah and Al Ain are monitored; the whole of the agricultural extraction, that for domestic use in the villages in the Northern Emirates and that of the desert foreland, is unmonitored. Added to this, agricultural water use is absolutely uncontrolled. The agricultural sector itself is highly subsidised and is not based on a successful economic system that takes into account the cost of the various input components, foremost among which is the cost of water; nor is it protected against the foreign import of such items, which is growing in volume.

In the vast area of the Arab World there are only 3 rivers of international standard on the basis of the volume of water discharge. These are the Rivers Nile, Euphrates and Tigris. All are sources of water shared by several countries and all pose dangers of strife for water rights in the near future. The upper sections of the Tigris-Euphrates are in Turkey which has ambitious plans in south east Anatolia involving the construction of 21 dams across the Tigris- Euphrates to enhance the generation of electricity and provide irrigation water that would increase the agricultural productivity in that part of Turkey by 17 times by the year 2000 (Uqba, 1991). Such multi-damming of the two rivers would reduce markedly their flow into both Syria and Iraq, with the flow into Iraq, estimated around 30 billion m^3/annum, is being reduced to only 11 billion m^3/annum. This would result in a water deficit as even the minimum irrigation requirements of Iraq of about 13 billion m^3/annum would not be met. The situation could worsen for Iraq should Syria also go ahead with its equally ambitious plans to exploit the Euphrates, which could leave Iraq with an immense water shortage in the coming few years that might put an end to the age-long dream of transporting 1.4 mcm/d.

In Egypt, weeds - water hyacinths - began to spread prolifically in the Lake Nasser. From there they have spread to almost all the drains, canals and natural water ways of Middle Egypt and Delta area (Abu-Alainine, 1979). Such a situation could easily occur in the reservoirs of Arabia, although weeds are unlikely to colonise natural waterways since outside Yemen and Tihama Asir none has a perennial flow (Al-Sharif, 1977). Nevertheless, weeds could become an ecological problem in new reservoirs although the precise nature of the problem is difficult to assess at the present time. However, one important factor which engineers in the area should bear in mind is that weeds do tend to cause vast amounts of water to be lost.

Egypt relies largely on surface water provided by the River Nile for its irrigation needs. The population is set to increase between 50 million to 70 million by the year 2000. Agriculture is currently based on extensive farming and is failing to satisfy the food needs of the country as is evident from the cost of food. The total water demand is about 73 billion m^3/annum, but the annual flow from the Nile is 68.9 billion m^3/annum, by no means all of which is safe for human consumption due to contamination (Uqba, 1991).

Large additional amounts of water must be flushed through irrigation canals in order to overcome the blocking effect of the weeds and ensure that adequate quantities of water pass along the channel. Large amounts of water are lost by evapotranspiration from the weeds. Again, at Lake Nasser, for example, it has been estimated that more than 2.857 billion m^3 of water are lost as a result of weeds each year (Al-Matari, 1981). Aquatic weeds could become a serious environmental as well as economic problem which could to some extent limit the likely success of some water resource development in Saudi Arabia.

1.2.2 Overview of Water Resources in Saudi Arabia

The need to consider the development and better management of water resources has arisen in Saudi Arabia as well as in other arid parts of the world. If any single resource on the national level in Saudi Arabia could be labelled the most important, it would be water, not oil. Most of the water made available to Saudis, no matter what the source, must be allocated for use in the most efficient way by use of agricultural, domestic, municipal and industrial consumers (MAW, 1981).

Water is a basic necessity for any type of development. The type and intensity of agricultural production, the location and density of human settlement, and the nature and level of industrial growth, in addition to other components of economic and social development, are subject to restrictions imposed by the current water shortage. The increasing urbanisation of the population has placed severe demands on the ground-water resources which are constantly being lowered by the proliferation of tube wells. Few, if any, of these wells are being recharged at a rate that will maintain them for use in the future. Aside from increasing urban use, most of the important agricultural irrigation areas in the country have been overpumping for many years. These wells supply not only agriculture with water, however, they also supply most of the demand for water of nearby cities, towns and villages, as is the case in the Eastern Province where most of the commercial and pilgrimage activities are centred.

In the longer term, however, the problem can really only be served by the introduction of more efficient irrigation methods such as those outlined in Chapter 6. However, attempts to do this have so far had only limited success. It seems that an important factor behind this is the fact that comparatively few real attempts have been made to educate farmers about improved irrigation technologies. Worthwhile as these efforts may be, they do seem to play only a small role in present day water resource development policies, with the main emphasis being placed on technological solutions to the problem. It is suggested therefore that much more emphasis be placed on a grass roots approach which would see farmers acquire a far greater knowledge of modern farming techniques which in turn would go a long way towards eliminating the problem of salinity. Extensive loans and grants from governments should be continued and even increased in order to facilitate improvements in irrigation and drainage systems.

As a result of this development, the standard of living has improved and the population has increased. The population increase is a result of both natural birth and by the immigration of hundreds of thousands of labourers to meet the labour-shortage within Saudi Arabia. The resulting increase in demand for water has placed a great stress on the already limited water resources (Al-Layla and Selen, 1986).

Despite the country's aggressive water development plans, which have concentrated on the development of groundwater, surface water, waste water, and the expensive technique of desalinating sea water, a severe shortage of water continues to exist. The shortage creates many restrictions and problems, primarily in the areas of agricultural, industrial, and domestic use of water.

Saudi Arabia is extracting groundwater in excess of 20.5 billion m^3/annum of which only 12% (2.5 billion m^3/annum) is from replenishable groundwater sources. The remaining 88% (18 billion m^3/annum) is mined from fossil groundwater in deep formations (MAW and Al-Ibrahim, 1991). Groundwater reserves in Saudi Arabia were estimated to be about 337.5 billion m^3, with a possible additional 160 billion m^3 from deeper aquifers. Given the present rate of groundwater extraction, total depletion of reserves could take place before the year 2000. Saudi Arabia is drawing groundwater from the upgradient parts of the same Dammam/Um-er-Radhumah aquifers that stretch into Kuwait, Bahrain and Qatar. In all these countries the groundwater imbalance is critical. There is, therefore, a hydropolitical situation between these four countries that has not yet been addressed bilaterally or through the aegis of the Gulf Co-operation Council. New water sources are sorely needed in order to meet the demands of these various sectors.

The Gulf countries are economically self-sufficient to some degree. Imported water clearly does not fit into a pattern of self-sufficiency; the notion of relying on the outside world for a commodity such as water, which is much more basic than wheat, or consumer goods, transcends the traditional rules of economics. Statesmanship and wisdom are the qualifications needed to judge whether water should be imported, just as they are needed to judge whether water should be mined.

The notion of towing icebergs to the shores of Saudi Arabia has stirred the imagination of many, particularly of those with a feel for the romantic and the unknown. The investigators have gathered information, from the published literature and through direct correspondence with some of the few knowledgeable experts in the very specialised field, in order to assess the state-of-the-art of the iceberg importation (MAW). This has indicated that few practical engineers and scientists see icebergs as the resource of the future for Saudi Arabia. Problems are foreseen of a technical, economical and legal nature.

The technical problems centre on the capture, transportation and delivery of an iceberg. The sheer magnitude of the ice masses will require transport modes not now in existence. Propelling an iceberg without assistance from, or even against, an ocean current has been described as an impossible task given today's power craft. Moreover, icebergs have a tendency of breaking up unexpectedly and of turning over, both circumstances which make towing or pushing a most hazardous enterprise (MAW).

It would appear that the pressing time frame is the main obstacle to a thorough assessment of the feasibility of iceberg importation to Saudi Arabia. Many aspects will require time-consuming experimentation: the time frame for solving Saudi Arabia's long term water problem does not allow for such experiments.

In Saudi Arabia, under natural, undisturbed conditions the loss components of the hydrological cycle are highly significant. Even with a minimal rainfall of 500 mm/y, less than 3% of this renewable supply is currently being utilized.

Water is a vital resource in any part of the world, but it is particularly important in arid lands such as central and northern Saudi Arabia, and it has a great impact on the way of life and the location of settlements. Shortage of water has played a primary role in determining the population distribution, agriculture and industry in the region.

Indeed, it was the lack of water which was the main cause of people leaving their homeland, seeking an easier life in places like the Arabian Gulf States or even as far as North Africa and India. In Bedouin communities, conflicts which would in the past arise over priority in obtaining water from an isolated shallow well were the cause of many deaths.

This drastic change in water use is most marked in the southern area of Saudi Arabia, where water is always in short supply. Most of the populations live in wadis of the southern area, and these mostly flow along the eastern slope of the 60 km long Asir mountains. The problem of water supply is made worse by urbanization. Throughout the country (including Tihama Asir) the flow of people from rural to urban areas has accelerated in recent years. In a period of five years (1980-1985), approximately 5,000 rural residents moved to cities. Water consumption per capita undoubtedly will increase in urban areas, although it may not be evenly distributed across socio-economic groups. Moreover, industrialization which accounts for substantial use of available water, and often contributes to the reduction of existing water supplies through contamination, tends to concentrate in urban areas as well.

Water in Saudi Arabia occurs naturally as surface water and as ground water. Water is also drawn from non-conventional supplies. These resources are under the jurisdiction of, and constant development by the Ministry of Agriculture and Water (MAW). Demand for water is connected with activities such as irrigation, agriculture generally, and domestic and industrial water requirements. Study of Saudi water resources began in the early 1950s, undertaken by a Saudi government commissioned team of United Nations experts from the Food and Agriculture Organisation (FAO). Several interesting publications of these studies can be found at the MAW. A brief summary of their main findings is presented below.

The Italconsult (1964) study examined average rainfall ratios in Saudi Arabia over a number of years. Based on this research, and on some other sporadic runoff values for the years 1954, 1959, 1960, 1961, 1962 and 1963, the report concluded in August 1966 that the annual run-off co-efficient varied according to whether the year was dry or wet. It was reported that the main water resources of the country were derived partly from wadis but mainly from aquifers - permeable tilted layers of rock, lying between impermeable layers, to which surface water percolates, and through which water often travels great distances. These produce shallow ground water resources which, with increasing demand, have become inadequate to meet the country's requirements.

Several studies on water resources in Saudi Arabia have concentrated on water resources required for domestic water supply and irrigation purposes.

The study carried out by Rizaiza and Allam (1983) suggested that the water demand in Saudi Arabia had increased from 1,750 mcm in 1975 to more than 8,600 mcm in 1985 and, at the same time, there had been an increased demand on supply for water recycling and desalination from 18 mcm to 605 mcm. Despite the fact that ground and surface water and recycled water were fully exploited, water supplies fell far short of the country's requirements. One consequence of the increased demand was that ground water levels dropped in several areas. The study also concluded that whilst the country has surface water, this cannot always be relied upon, as quantities vary sharply from year to year.

In Saudi Arabia the present approach to meeting the high, and ever-growing, demand for water is by exploring alternative sources of water supply. For instance, water is imported, and more desalination plants are being built using the unlimited quantities of seawater to supplement increasingly scarce groundwater.

In the Fourth Development Plan (1985), the MAW estimated future water requirements for various sectors - rural, urban, industrial and agricultural.

A study carried out by Raphael and Shaibi (1984) concluded that a surface water supply is one of the most essential resources required to maintain a viable agricultural or urban society. Under the guidance and encouragement of government, economic development in Saudi Arabia has progressed to the point where foreign labour is required to meet the growing demand for industrial, agricultural and urban expansion. With increased technology and diverse economic development in emerging countries there is often rapid growth of urban areas. This in turn requires a readjustment or change in the sources, volumes and distribution of existing water resources.

As development occurs, the demand for water in urban residential areas increases. In this investigation water resources in the rapidly developing cities of Saudi Arabia, such as Al-Taif, are examined and the study includes examination of the urban development and associated organisational problems faced by such cities. In many ways the problems of cities such as Al-Taif are mirrored in other areas over the whole of the Middle East. However, its geological situation, together with its remoteness from bedrock aquifers and the Red Sea, add to its problems. In the past local, unconfined ground water supplies have been sufficient to serve the needs of the local population. However, recently, with increasing demand, more remote water resources are having to be investigated and exploited.

The research of Al-Ibrahim (1991) concluded that Saudi Arabia is an arid country with limited water supplies. Rainfall is scant and there are no lakes, rivers or streams. Faced with a steadily rising demand and inadequate and unreliable resources of surface water, the country is increasingly dependent on that ground water which receives very limited natural recharge and is classified as fossil or non-renewable water.

When the rate of withdrawal of water from groundwater sources exceeds recharge, mining of ground water occurs which can cause a variety of problems such as fast depletion of ground water supplies and deterioration of the quality of water. Ground water is Saudi Arabia's most valuable water resource and its rapid depletion and deterioration in quality threatens to have serious socio-economic implications.

Surface water, due to low precipitation and high evaporation rate in the country, is limited in supply. Considerable quantiites of surface water are wasted through run-off in rainstorms: estimated at between 2000-2400 mcm per annum.

Groundwater in Saudi Arabia is under threat as the absence of a reliable and adequate supply of surface water has led to an increasing demand on ground water resources. The quality of ground water resources in Saudi Arabia varies from area to area but most can be classified as brackish and contains over 1000 ppm of total dissolved solids (TDS).

1.2.3 Background hydrology of Saudi Arabia

The hydrology of Saudi Arabia is essential if one is to understand fully the many aspects of its water resource development and many of the associated problems. Due to the aridity of the region which has been described above, the country lacks perennial lakes and streams, and consequently groundwater has traditionally been the only reliable source of water. Even today, despite the advent of desalination, the bulk of Saudi Arabia's water supplies still originate from subterranean aquifers. As will be discussed below, the bulk of the country's water supply, as well as water resource development, is from fossil water reserves. It is extremely difficult to measure water extraction rates accurately, and there is still a great deal of controversy over the magnitude of groundwater recharge, and although the recharge/extraction ratio will vary from aquifer to aquifer, the consensus of opinion does seem to accept that in most areas of the country water extraction rates are growing to such a level that in effect water mining is now occurring. Unfortunately, the government of Saudi Arabia does not seem to appreciate that this is occurring, all of which is likely to lead to problems in years to come. Provided it is fully realised that groundwater is being mined and provision is made for the eventual exhaustion of the supply as an economic proposition and the redeployment of the people, the mining of fossil groundwater is not objectionable in itself. The danger arises when non-renewable groundwater is mistakenly considered and treated as a renewable natural resource.

Given the foregoing, it can be seen that the hydrology of the country is a central consideration to any study of water resource development in the area and of the problems being experienced and likely to be experienced in this field. Consideration will therefore be given to the nature and extent of the groundwater reserves (see Chapter 4).

With such low precipitation totals and high evapotranspiration rates, no perennial rivers exist within the country. Surface runoff, however, frequently occurs during the rain season when flash floods develop in response to intense rainfall. Such spates are highly erosive in the upper portions of drainage systems, giving rise to the deposition of large gravel spreads where the wadis broaden to meet the lowlands. Under these conditions, damage to irrigation networks, crops and houses sited along wadi floors can be considerable (Chapter 3).

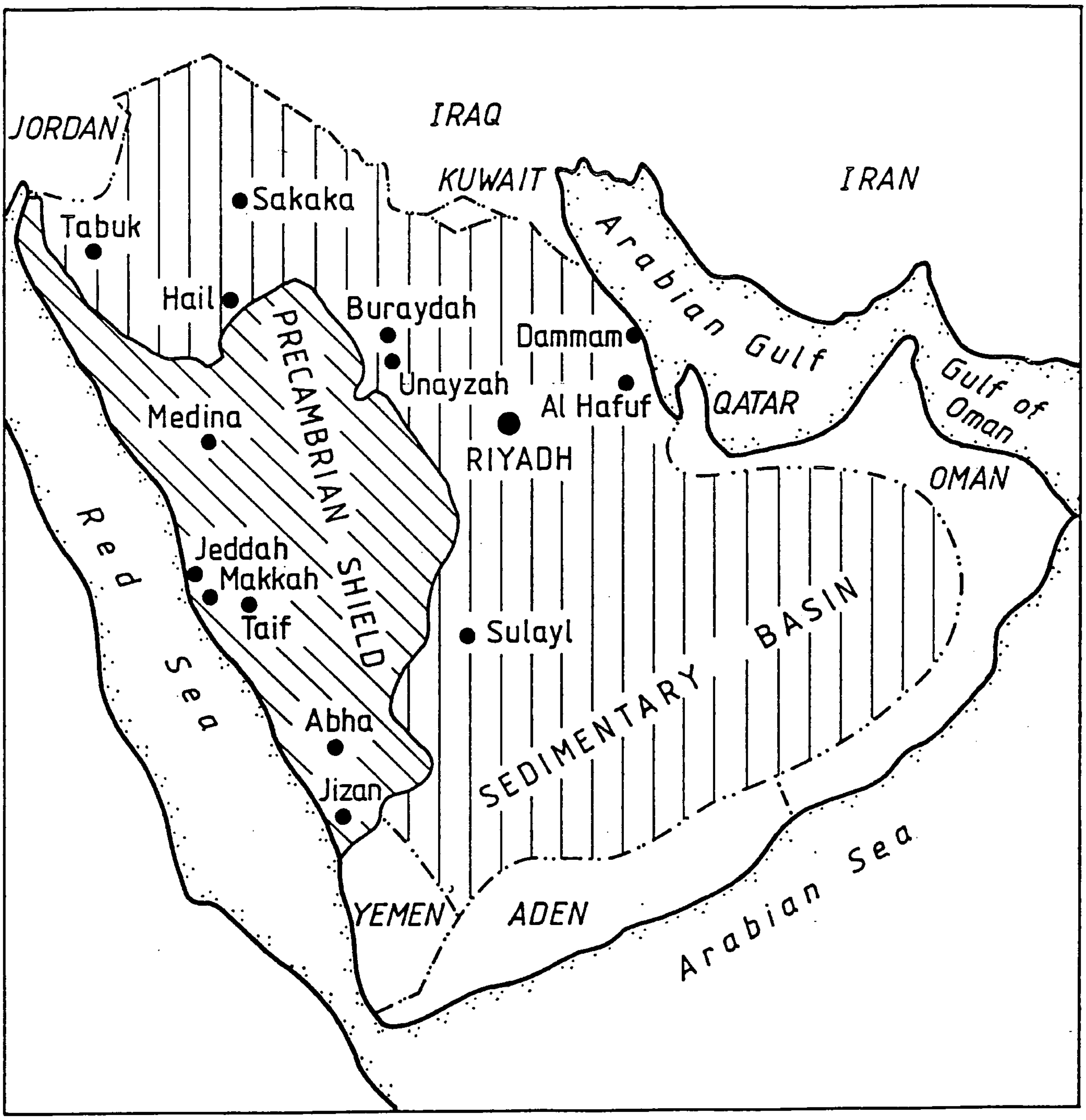
The watershed along the western highland edge of the plateau separates two distinct hydrological regions. The western scarp slope is dissected by many short, steep water courses flowing into the Red Sea, a few of which are perennial, though also very limited. In the wet season, in the form of more cloudy days with few but often very heavy rains, these watercourses carry torrential streams. Some of these have been sufficiently powerful to cut back through the plateau edge and to capture the upper courses of streams formerly flowing east, the best example, being the Wadi al Hamd. Eastwards the drainage in general follows the gradient of the massive surface, in less numerous wadis, usually broad shallow depressions, none carrying permanent water. Much of the drainage from the plateau is in the subsurface. Because of the distinct seasonal nature of the rainfall, water resources are tapped by pump irrigation and artesian wells in the eastern part of the plateau, and by the distribution of the flash floods and stored water from reservoirs in the western part of Saudi Arabia.

Certainly Saudi Arabia does have vast groundwater resources, but the quality and quantity of the water is highly variable and, as discussed below, only occasionally does good quality groundwater coincide with areas of good quality soils or urban demand. Moreover there can be little doubt that the present groundwater extraction represents the mining of a finite resource and as such these supplies will become depleted some day, sooner or later.

People in the Arabian Peninsula have relied for thousands of years on the scant rainfall to provide water for their livestock and to maintain their limited agricultural activities. Because there are no perennial streams or lakes in Saudi Arabia, the lack of reliable surface water has forced dependence on groundwater reserves.

Geologically, Saudi Arabia consists of two main areas: the basement complex in the western part of the country and sedimentary formations in the eastern part (see Figure 1.1). The basement complex was formed largely by igneous and metamorphic rocks of the pre-Cambrian age (Arabian Shield). The complex's groundwater, which can be tapped by shallow wells, may be found in patches of alluvial deposits and under wadi deposits. Large parts of the Hijaz region rely on this source to supply them with water, as in Jeddah, Makkah, and in the Asir region.

Figure 1.1: Sedimentary Basin and Western Precambrian



reference: Hijaz Land and Population

The sedimentary formations in the eastern part of the country are the main sources of groundwater in the eastern, central, and northern parts of Saudi Arabia. Two thirds of the country is underlain by sedimentary formations mostly of sandstones, limestones, shales, marls and alluvium. Sandstone and limestone formations are the main sources of groundwater (see Chapter 4).

The rainfall in the country is very low and unpredictable, runoff is irregular and storage of surface water is almost negligible. Generally the rainfall alone is insufficient to meet the needs of agriculture. There are no perennial streams in the proper sense. Floods occur but they are usually quite local and the water travels for a few kilometres and then disappears into the dry wadi alluvium. Floods in the Asir regions along the Red Sea coast rarely reach the sea (see Chapter 3).

The water resources studies (MAW) have located many aquifers with large amounts of stored water, but earlier discoveries of such water led to hasty drilling and uncontrolled extraction from many wells, with little regard to the water requirements and drainage facilities of the land they served. Furthermore, the enhanced status conferred on an individual through ownership of a well has had an important bearing on the number of wells constructed. The design of the earlier type of shallow hand-dig well imposed limitations on the quantity of water it could supply and hence the extent to which its use could be shared.

With the increase of population, the expansion of industry and irrigated agriculture, and the draw-down of groundwater levels, particularly in the coastal areas, desalination plants are built to supply these areas with good quality water for domestic use and for industry. The water resources in Saudi Arabia are following:

1. Surface water (Chapter 3).
2. Groundwater (Chapter 4).

3. Desalination plants (Chapter 5).

4. Reclaimed waste water (Chapter 5).

For this reason, shortage of water has reached a critical level in Saudi Arabia. To manage this crisis, two alternatives avail themselves: to find another source of water to fulfil the demand; and/or to increase water use efficiency (MAW, 1981).

Availability of water is a universal problem. It is more severe in areas such as the north and centre of Saudi Arabia. In many regions of the world, new sources of water are being sought in order to develop agriculture and generate more electricity, a principal source of energy for industry.

Recent water resource studies have located many aquifers with large amounts of stored water, but earlier discoveries of such water led to hasty drilling and uncontrolled extraction from many wells, with little regard to water requirements and drainage facilities of the land they served. Furthermore, the enhanced status conferred on an individual through ownership of a well has had an important bearing on the number of wells constructed. The design of the earlier type of shallow hand-dug well imposed limitations on the quantity of water it could supply and hence the extent to which its use could be shared.

Later, artesian sources of supply brought changes in the methods of water used and unwanted water ran to waste after the owner had irrigated his land. This uncontrolled water use created many new problems affecting the productivity of agricultural lands. With the increase of population, the expansion of industry and irrigated agriculture, and the recharge to water table draw-down effect of ground water levels, particularly in the coastal zone, desalination plants are being built to supply these zones with good quality water for domestic use and for industry.

The MAW is promoting projects to conserve available water, strictly controlled to avoid waste, and hundreds of new wells have been drilled. Seawater is increasingly being put to meet urban demands.

The investigation of possible alternative water sources is being undertaken by the government. Whilst the desalination of seawater is a partial solution, it can be expected to provide only a fraction of total needs. Desalination is, therefore, only a part of a total programme of water resource development.

The MAW has embarked on an ambitious programme of water conservation and dam construction. The government has already built more than 170 dams in various locations in Saudi Arabia to store water and make possible the cultivation of dry land. Another aspect of the water programme is the construction of irrigation canals.

Interest in the solution of the water crisis is high since the use of sizable quantities of water is of importance to a number of interest groups. There are, in addition, high hopes that an examination of the possibilities for exploitation of more distant water resources might reveal opportunities for further development.

1.2.4 Water Scarcity in Sauid Arabia

The reason why water is scarce in Saudi Arabia is because rainfall is very low and unpredictable. Run-off is irregular and storage of water is almost negligible. Generally, rainfall alone is insufficient to meet the needs of agriculture. There are no perennial streams in the Saudi Arabia. Floods occur, but they are usually quite local and the water travels for a few kilometres and then disappears into the dry wadi alluvium. Floods in the Asir region along the Red Sea coast rarely reach the sea, thus the ground water is of great importance for agriculture. Two thirds of the country is underlain by sedimentary formations, mostly of sandstones, limestone, shales, marls and alluvium. Sandstone and limestone formations are the main sources of ground water.

The increasing urbanization of the population has placed severe demands on the underground water resources which are constantly being lowered by tube wells, and a few, if any, are being recharged at a rate that will maintain them.

In addition to increasing urban use, most of the important agricultural areas in Saudi Arabia have been overpumping for many years. These wells supply not only agricultural land with water, they also supply most of the demand for water for nearly all the towns and villages, as in the case in the Eastern Province where most oil wells are located and in the Hijaz and Tihama Asir.

Considerable effort and research are required to locate and utilize underground water supplies which at present supply most of the fresh water consumed in the country. The government has recently taken steps to ascertain the underground water's usable storage capacities, flow rates and potential yields. The need for control of water use and recharging where there is a significant decline in water levels is also recognized.

With the advent of economic development and its effect on the local population, the seriousness of water shortage has been more widely appreciated by the public. The investigation of possible water sources is being carried on by the government. One of these is desalination.

Water is used for domestic and industrial irrigation in Saudi Arabia. The Saline Water Conservation Corporation (SWCC) gives figures for per capita water demand on a regional basis.

1.2.5 Domestic/Industrial and Horticultural Water Use Projections

The agricultural sector is an important element of the Saudi development process. Indeed, agricultural development is regarded as an integral part of economic diversification, reducing long term dependence of the economy on the single commodity of oil, a dwindling asset. Agricultural development remains a vital element in the overall Saudi development process for other reasons.

The significance of water to the agricultural development of the mostly arid Saudi cannot be over-emphasised. However, water is also needed for drinking, for domestic use or personal consumption and for industrialisation. Saudi Arabia embarked on gigantic projects for massive industrial development because industrialisation is a critical factor in cushioning the eventual end of governmental revenue derived from dwindling, non-renewable hydro-carbon assets.

Although the existence of many water short regions is undeniable, there are areas where misuse of water is creating shortages where none need exist.

Against this fluctuating background, the investigators have gathered relevant projections and assessment, and they are confident that a true use-projection has been derived within a fairly narrow band of uncertainties.

The indicator variable referred to under urban demand represents an effort by the author to account for a jump in oil revenues as well as other variables directly and indirectly related to the increase in oil revenues in 1974, and it was given a constant value from 1973 onwards. The use of such a variable, although simple and expedient, throws doubt on the resulting projections in the case of there being any unexpected increases in oil revenue, which continues to be the only significant economic resource of Saudi Arabia. Even though an allowance was made for Saudi's lack of experience in that field, it is doubtful that local industries will reach even a level of 50% of the projected target, since the most important driving force for conservation, a strict system of water charges, is not yet in place (MAW).

Water for the two different uses is generally delivered through different distribution lines, with domestic/industrial uses being metered so its costs could be recoverable from identifiable users/customers. A simple technical solution to the quality problem is to construct multiple treatment/distribution facilities, which would satisfy the objective of matching quality demands.

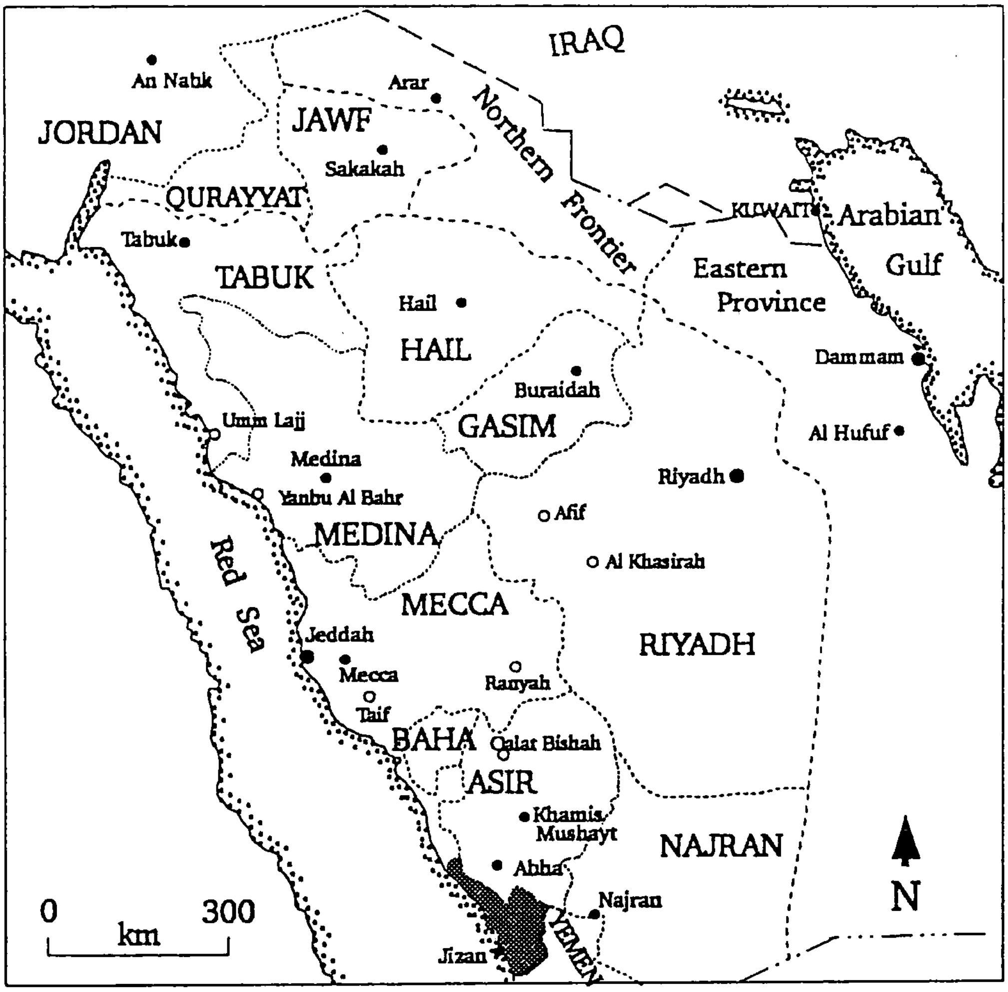
For the purpose of this project, it is assumed that true domestic municipal/industrial uses are equal to 48% of the total municipal projections and that the other 52% portion is used for horticulture.

1.2.6 Overview of water resources in Tihama Asir

The Tihama Asir plain varies in width from 30 to 40 km and is bounded on the east by a rugged mountainous wall of igneous and metamorphic rocks which rises to something over 5000 m above sea level. The plain is interrupted at its southern extremity by mountains. The coast is sealed off from deep water by a continuous coral reef that severely restricts the establishment of ports and the development of marine activity. The study area is presented in Figure 1.2, and is characterised by numerous wadis which lie at the extreme end of south Tihama and drain into the Red Sea and offer a combination of climate, soil and water suitable for domestic use and agricultural irrigation.

The region stretches along a 225 km coastline. It is composed of a coastal plain covering approximately 8000 km^2, and a mountain range which reaches more than 2000 m in altitude. It occupies an area of about 14,000 km^2, and is the sixth most populated region among the fourteen regions of Saudi Arabia. Jizan, the main city,

Figure 1.2: Tihama Asir study area in Saudi Arabia



Limits of Administration Areas

The Tihama Asir Administration Areas

is located on the Red Sea about 60 km north of the Yemen border. It lies approximately 550 km south east of Jeddah and roughly 950 km south west of Riyadh.

Following rainfall, the precipitated water undergoes one or more processes. For instance, it can evaporate, escape to the sea, be absorbed by vegetation, or refill underground aquifers. The corresponding proportions can be controlled by man through the construction of reservoirs, irrigation canals or other methods. The present estimates of average annual water resources, in million cubic metres (mcm), including the Malaki Dam and Wadi Jizan irrigation works, are as follows:

	mcm
Malaki Dam Recharge	80
Natural irrigation flooding	427
Annual surface flow	507
Inflow to Aquifer from:	
Flood irrigation	63.5
Controlled irrigation	34.6
Net potential extraction from Aquifer	98.1

Of this estimate of 98.1 mcm, only 77.7 mcm are extractable by pumping and available for competing agricultural and urban uses.

At present Tihama Asir obtains various amounts of its water from the following resources:

(1) Shallow ground water aquifers. These have traditionally been the principal water resources of the area. The shallow aquifers are unreliable and insufficient to meet the increasing water demand because recharge of the wadi gravels depends entirely upon local water flow. Water is piped direct from the wells. Shallow aquifers include Wadis Jizan, Baysh, Damad, and Sabya and its tributaries.

(2) Surface runoff: This contributes greatly to the water supply and is considerably utilized mainly for agricultural uses.

Rainfall intensity and the duration of storms, along with their hydrographs and the existing and proposed long and short term plans for Tihama, and its catchment, have been studied in this research. Five wadis contribute to the surface run-off in Tihama: Wadi Al-Borda, Wadi Al-Khashabat, Wadi Haraba, Wadi Jizan and Wadi Mishref. They receive a mean annual rainfall of 63mm, delivering 1050 mcm/y to the area territory. Greater collection from these wadis would thus constitute a major contribution to correcting the water imbalance. On the basis of earlier resources surveys, it is estimated that the following amounts replenish the Tihama Asir's waters:

- Direct surface runoff: 7560 mcm/y
- Recharge of shallow alluvial aquifer: 2220 mcm/y [Source: MAW]

This study covers infiltration rates at different locations and catchment areas; runoff coefficient values for Tihama's wadis, such as Wadis Jizan, Baysh and Sabya; measured and/or estimated sediment discharge in the area; the available hydrology of the Tihama area including an inventory of the wells observed in Wadis Jizan, Damad, Figa, Amlah and Khums. The study also covers the ground water levels and their daily, seasonal and annual variations, as well as aquifer characteristics, extent, depth and recharge.

The greatest volume of runoff in Tihama was found to be from the Asir mountains. The infiltration of rainfall into the ground to aquifers is controlled by many factors and it is greater beneath the wadis because their texture is characterized by high permeability. Most of the rain falls on the Red Sea escarpment and at higher and cooler altitudes.

The Tihama Asir people traditionally depended on shallow wells and seasonal rainstorms for their water supply. Both the quantity and quality of water were poor and the supply was irregular. The problem was endless as strains on water supply continued to increase with rapid economic development and population growth in Tihama Asir. Desalination of sea water in Tihama Asir will be developed in order to meet the increasing demands without much consideration for other concerns and water use management. The question is: what happens to such new resources? Moustafo Noury, Director, Branch of the Ministry of Agriculture and Water in Jeddah, considers potential future resources. Noury points out that "reserves" should be considered: "We cannot close down these wells as they will clog. You must operate them from time to time. The same is true of the treatment plants" (Harvey, 1980, page 22).

For this reason, appropriate solutions to water problems are proper water management and careful conservation to accomplish maximum utilization. It is vital that the need of Tihama Asir for desalinated water be investigated, in order to develop the water supply to the maximum level possible.

The demand for water is constantly rising in Saudi Arabia generally, and in Tihama Asir in particular, as a result of an unprecedented increase in the population and the new developments in industry, agriculture and urban centres. Dwindling water reserves are raising the status of water from a free commodity. Of the many findings that have emerged from these explanatory studies, the site selection requirement for the development of water resources deserves further investigation mainly due to the large variability of rainfall and poor logistical support.

The selection of water resources in Tihama Asir, as a subject for study, may be justified in the light of the following considerations: (a) there is insufficient rainfall in Tihama Asir; (b) rainfall occurs sporadically as short isolated flow periods separated by longer periods of lower or zero flow; (c) in water uses, such as domestic consumption and horticultural irrigation, there appears to be much room for simple reduction in demand without creating serious hardship.

Tihama Asir has two main water resources: surface water and groundwater. Floods occur during the rainy season, but their distribution through the year does not follow a uniform pattern. The annual flows vary from year to year, and floods number from 15-33/year with a volume of 0.5-10 mcm/flood. In addition to the surface water, the groundwater is of significance for irrigation in the area. The groundwater in the area proves the presence of an aquifer underlying almost all the wadis. This aquifer contains an estimated 5000 mcm of groundwater. The aquifer is fed by percolation from flood spates through the wadi beds and from neighbouring wadis. Smaller runoffs also have a recharge effect. The major aquifer of wadis are in the alluvial deposits with thicknesses varying from a few metres overlying lava flows, up to 100m in the centre of the wadis with an associated groundwater table which varies from a depth of 10m below the wadi beds, up to 20m below ground level. This aquifer consists of heterogeneous alluvial deposits, involving rocks, shales, and sandstones covered by the alluvial sediments added by floods. Finally, studies with respect to groundwater quality, state that areas of least salinity hazard occur at the eastern end of the wadis, salinity increasing down the wadis toward the coast.

In Tihama Asir, the distribution of available water resources can be guessed at by tracing the populated areas, where a fair amount of water is likely to be in use. The two major water sources identified in the area are:

(1) Rainfall: terraced farm land in the Tihama Asir, and foot-hills (see Chapter 2);

(2) Wadi water (runoff): the wadi quadrangle, Jizan, Baysh, Sabya and Dammad, mostly by wells tapping sub-surface (groundwater) flow, and by means of surface flow of floods (see Chapter 3).

Rainfed terraces in a patchwork pattern have been commonly used for water storage in the wadi quadrangle for a long time. Further evidence of water use, beyond the centres of population, is the considerable extent of irrigation by making earthen barriers across a wadi basin. Runoff from wadis has been difficult to quantify, despite efforts made by the governmental agencies to measure the water level of wadis of many locations, however, at least one example of runoff measurement in the area is available - the operation records of the Wadi Jizan Dam. The behaviour of water table in the reservoirs clearly show the runoff rate together with discharge and various kinds of loss by evaporation, infiltration and leakage.

1.3 Key factors controlling water use

The development of water resources is determined by a complex pattern of demand and supply. Population growth, living standards and economic development determine the quantity and quality of water demanded from a high-quality piped water supply; and agriculture has been making increasing demands for irrigation water. There has been a significant shift in the demands of the three end users: domestic, agricultural and industrial development. Each of these is examined below.

1.3.1.1 Population and development growth in Saudi Arabia

The most recent nationwide population census was conducted in 1974. That census indicated a population of 7.013 million people. More recent estimates of the population size tend to differ markedly. However, the Ministry of Finance and National Economy estimated that the population was 10.1 million in 1406h (1986). Moreover, all estimates agree on one important feature: a annual population growth rate of about 3%. This growth rate is probably for the rate of natural growth of the Saudi population (as distinct from migration). A high birth rate and declining death rate (among the young) implies that an increasing proportion of the population is under 15 years. In a region that venerates the elderly, relatively few elderly people are to be found. The social implications of the disproportionately large population of young people are hard to overestimate.

The high population growth rate places an increasing demand on the water supply. In order to examine this demand, it has been necessary to make a number of assumptions.

The Ministry of Finance and National Economy was expecting the population count to be 11.7 million in 1405h (1985) and 13.5 million in 1410h (1990).

The first census indicated that some regions had larger population than others. The Western Region, for instance, which boasts a large cultivated area, had a population of about 1.5 million. In the Northern Region, where the cultivated area is small, the total population was 100,000. The population of the Central Region was between 1 million and 1.5 million.

The population growth rate in the Western Region is higher than average, and in the Northern Region is lower. The two variables of regional population and regional population growth rate are not linked in any obvious way. For instance, in the Eastern Region, its percentage of the total Saudi population ranks it higher than its percentage rate of population growth.

1.3.1.2 Population and development growth in Tihama Asir

Since the last estimate in 1974, the population of Tihama Asir has increased at an annual growth rate of nearly 11% from 118,900 inhabitants to 137,000, an overall growth of 58%.

Population forecasts have been reported in the 'Strategy Statement and Regional Master Plan'. Estimates of the future urban population have been based on the assumption that urban populations will grow at higher rates than rural populations. This growth will be more rapid where basic employment is related to regional government and regional trade.

1.3.2 The development of agriculture

The agricultural situation underlines the extreme imbalance between the growth in demand for water and its supply. This is in stark contrast to the overall success of the agricultural sector. Agricultural irrigation has traditionally been the major water use sector throughout Saudi Arabia, usually in the range 80-90%. It is interesting to compare projections for development of agriculture and development of water in Saudi Arabia.

The investigators had the opportunity to review agricultural statistics on irrigated crop lands. This called for a revision of the water demand calculation and the revised values projected towards the year 2000.

The agricultural sector in Saudi Arabia has the potential for significant growth. Each year local production meets an increasing percentage of the country's food needs. The cultivated areas of Saudi Arabia have been developed wherever water has been plentiful. The country's existing irrigation systems are currently being modernised. These and other developments are a far cry from the hand-dug irrigation canals of the past, and are helping to make agriculture in Saudi Arabia a more efficient and productive enterprise.

The government involvement in accelerating domestic production has been achieved through the means of various approaches to agricultural development. This has been done by providing the required capital, by means of easily available credit and intensive subsidies, and other required inputs and services such as free farming land, extension, research, training, cooperatives and marketing infrastructure. The government has also taken full responsibility for initiating and running large development projects such as desalination plants, dams, irrigation and settlement schemes.

Saudi Arabia has taken the important first steps necessary to become a net exporter of food, and is moving towards a position whereby it can meet the population's growing water needs. Saudi Arabia can look confidently to its future as a self-reliant food producer and a nation with a secure and plentiful supply of water.

1.3.3 Industrial development and growth

The government's economic plan is for diversified industrialisation, and the development of hydrocarbon-based energy-intensive primary industries based on the use of Saudi Arabian natural resources to their full potential. These industries were to be restricted to coastal locations where their large water requirements could be supplied by desalination plants.

The Saudi Arabian government, recognising that oil and gas are non-renewable resources, developed a programme of comprehensive large-scale industrialisation to diversify and manufacture other products for domestic use and export, thus providing a new base for continued Saudi Arabian economic growth and stability.

Industrial demand was related to:

- projected production of various products;
- water intake by production units;
- a projected reduction factor.

The indicator variable referred to under urban demand represents an effort by the author "to account for this jump in oil revenue as well as other variables directly and indirectly related to the increase of oil revenues in 1974" and was given a constant value from 1973 onwards. The use of such a variable, although simple and expedient, throws doubts on the resulting projections in case of unexpected increases in oil revenue, which continues to be Saudi Arabia's only significant economic resource.

The investigator selected an approach that combined the Ministry of Finance and National Economy (MFNE) population estimates, and the Development Analysis Associates (DAA), the Saline Water Conversion Corporation (SWCC) per capita demand rates, each of which was available on a regional basis. This ratio varies considerably from region to region. It was concluded that the aggregate national division should be 48% domestic/industrial. Although the development suggests a need for caution.

The parameters of most interest are the projected growth patterns of domestic/industrial demand, and the consequences in terms of groundwater mining.

The use of water for industrial purposes increased significantly in four major development sectors: oil production, large industrial complexes, mining and seaport industries. There are, of course, many other industrial uses of water in Saudi Arabia.

1.4 Purposes of this study

The purposes of this study are to investigate all current water resources of Saudi Arabia as a whole, and to analyse them geographically and economically to determine their potential abilities to meet increasing water demand as related to water exploitation costs, to investigate the extent and nature of the growth in water demand, and to consider the methods and technologies which are being used. The study will additionally focus on the province of Tihama Asir.

Given that the country has its own unique backdrop of social, economic and hydrological circumstances, in terms of water resources, there are climatic, soil, vegetation, economic, and hydrological aspects of all areas to consider. Aspects common to all provinces include the paucity of precipitation, surface water (lakes relating to perennial wadis), and groundwater (aquifers and wells); a rapid growth in water demand largely as a result of both direct and indirect effects of oil developments (the discovery and exploitation of mineral oil in commercial quantities has precipitated considerable economic development); and the ability of all those in Saudi Arabia to spend large amounts of money on developing and using the most modern water production and gathering techniques.

One of the values of undertaking a study of water resource development in Saudi Arabia and Tihama Asir would seem to be that amongst the Gulf countries they represent a kind of microcosm. Saudi Arabia utilises all the most modern water development technologies such as desalination and sewage treatment systems. Generally lacking the financial constraints of other economically developing countries, Saudi Arabia has been able to construct and operate new water production and management systems on a much larger scale than elsewhere in the developing world. In the long-term, however, many developing countries see the large scale introduction of the new technologies, such as desalination, currently available in only a few areas, as a means of reducing their water deficits. In this sense it is hoped that this study might be of interest to those concerned with water and development throughout and beyond Saudi Arabia and Tihama Asir.

This study examines the feasible options for water resources in Saudi Arabia, and water resources development activities, with particular reference to Tihama Asir province, taking into account criteria of acceptability as defined by local constraints, and considers the preferences of concerned decision makers. There is also a focus on more specific, comparative assessments of various resources and uses.

Another intention of the study is to demonstrate the importance of the ground water withdrawal and use management. It is certain that Saudi Arabia in general and Tihama Asir in particular suffer greatly from the deficiency of natural fresh water. The water shortage problems are seriously aggravated by the existence of private wells tapping the same aquifers. Modification of water use from agricultural to domestic uses in areas within and around the wadis would undoubtedly reduce water shortage problems. The accomplishment of this purpose will assist the Saudi government in formulating new master plans for future water needs.

The overall purpose is to review the existing major water resources and programmes in Saudi Arabia and Tihama, and to evaluate them in order to measure their types and significance of effects within the process of water development. More specifically, this study aims at:

(1) providing an overview of the current water resources status of Saudi Arabia and Tihama Asir;

(2) evaluating the Saudi government's efforts to produce artificial supplies;

(3) assessing the performance of domestic water demands and its contribution in Saudi Arabia and Tihama Asir; and

(4) identifying and recommending future directions and changes in Saudi and Tihama Asir water planning.

The reason why the demand for water in Tihama Asir is constantly rising is the unprecedented increase in population and further development in industrial, agricultural and urban land use, coupled with dwindling renewable reserves in the form of rainfall and run-off. A major emphasis is placed on three broad areas:

(1) water uses;

(2) water availability;

(3) multi-objective planning aimed at integrating resources and uses.

1.5 Significance of this study

The importance of this study derives from the fact that water resources in Saudi Arabia and Tihama Asir are limited, whereas the demand in all water use sectors is ever increasing.

The objectives of this study are to delineate the water resources development in Saudi Arabia and to describe the impact the population growth and development of agricultural irrigation, to address the water crisis which is impending if supply and demand are not brought into balance, and to describe what action needs to be taken.

To increase the sustainability of water resources and the efficiency of water use, it is essential to devise an optimum overall plan for developing the country's limited water sources. This plan should include the re-use of waste water and drainage water, better use of irrigation water through more efficient and economical irrigation methods, and optimum use of unpredictable flood water in the wadis by constructing more dams. These measures would not only add new sources of water, but would decrease the rate at which non- renewable groundwater is being depleted. As identified in support of the objective, they deal with more specific, comparative assessments of various resources and uses. The water resources in Saudi Arabia (surface water, groundwater, desalinated and re-used water), and the present and the future water demands are presented and discussed. A comparison between potential supplies and water demands under present and future conditions are made.

Specifically a study of water resources development in Tihama Asir, this study is similar to other academic studies in addressing some broader and more general issues. However, the main target of the study is to provide an explanation for the present of water resources development in the area. Whilst total water resources may be theoretically sufficient to satisfy world demands, water quality, economics, public attitudes, and agricultural irrigation may impose limits on the extent to which those resources can be employed. Planning systems are the means by which the utilisation of water resources for urban/industrial purposes and agricultural irrigation are channelled.

The basic argument in this study is that the development of water resources in the area is stimulated by the influence of urban/industrial uses and agricultural irrigation. The effect of floods (high runoff rates), which destroy everything in their path, has been to institute a dam construction programme. Dams such as Malaki Dam in Wadi Jizan are used to control floods, and to recharge ground water. The study discusses the surface and ground water resource potential of Tihama Asir, and present and future water demands.

1.6 Methodology, sources of data and problems encountered

The methodology employed in this study allows for the evaluation of the development of the water resources and planning efforts in Saudi Arabia, and specifically in Tihama Asir. The demand for potable water has led to the development of a number of major water projects, including the construction of immense desalination plants on the east and west coasts. A comparative study between all current Saudi Arabia and Tihama Asir groundwater resources, in terms of their hydrologic and geographic conditions, clearly shows what other alternatives should be considered. Most of this study is based on the author's experience in the Ministry of Agriculture and Water (MAW), and on official documents and reports during a field study in 1988-89 to collect data and discuss the problems with the planners. The data were collected from several government offices and universities, such as the Ministry of Municipal and Rural Affairs (MMRA), Department of Town Planning in Riyadh, and the branches of the MAW in Jeddah and Jizan, and Hydrology Department in Sabya, as well as the Saudi Arabian Water and Sewage Department in Jeddah and King Fahd University of

Petroleum and Minerals, King Saud and King Abdul-aziz Universities. In addition field visits were made to a number of projects, such as an irrigation development in Wadi Jizan and Malaki Dam, an irrigation development in Al-Hassa area, and desalination plants in Jeddah and Al-Wajh. Therefore, additional information has been obtained from published and unpublished external sources of books, articles, dissertations, documents and reports.

The analytical aspect of the study's methodology has involved two efforts. First, analysis of time-series data concerning some of the major water resources developments, whenever the availability and adequacy of data has permitted; and, second, analysis of quantitative data obtained through a field research survey conducted by the author and some colleagues during a field visit to a sample area in Tihama Asir, and other country areas. This data has been employed to make comparisons by expressing, in tabular form, data relating to groundwater, and development of water resources for domestic, irrigation and industrial uses.

For research purposes, water resources in the Tihama Asir area were divided into two sections, the north and south. Subsequently, about 50% of the villages in each part were randomly selected for intensive polling, and a sample of 27 out of 55 villages were utilised.

There were few difficulties encountered in the field work, and the task was completed according to schedule. However, with respect to the data collected, there was a severe lack of available data on water resources, area size and income, and population. Consequently, only limited information is given in this study on such topics, whether taken from previously published reports, or personally collected data. Another slight difficulty was encountered with base maps for the area of Tihama Asir. All the maps gathered had been compiled primarily from uncontrolled mosaic. A framework has been provided by the distinctions between natural water supply, settlement and population, and economic life. Attention has been focussed on concrete and important problems; factors relevant to particular problems are identified and solutions sought.

Also in the field, a portable tape recorder proved useful. However, taking notes of conversations was usually more appropriate, because of apprehensions of those who were being interviewed. Photographs, although costly, have been taken extensively, not only to provide illustration, but also to support statements which may seem either exaggerated or fictitious. A continuous supply of fresh information on recent events, and of new data have helped to keep this work as up to date as possible.

The wadi well-fields tend to be located within 40 km, but maybe up to 80 km, from the cities. Pipe construction costs between the wells and cities' water storage tanks usually increases with distance. During the field work, a visit to the local people (farmers and workers with the MAW), many questions were asked about the agricultural activity and problems, cultivation methods, water distribution and rights, and land tenure systems in the Tihama Asir area.

Areas of responsibility were identified for the deteriorating groundwater resources and the rapid escalation in the production of the non-conventional water resources. Several vital questions were answered that have always bewildered officials and the interested public relating to the actual state of the water resources, particularly questions about the amount of runoff. In addition, many other details have been exposed through this study: the quantification of groundwater extraction for agricultural irrigation; the overall interplay of the climatic elements affecting water resources through precipitation and evaporation; the geology and hydrology of the whole country and their relation to water resources; surface runoff and its actual contribution as recharge to groundwater; the volume of water involved in the recharge of the groundwater system from direct rainfall, surface runoff and subsurface flow; the types of water currently used by agriculture, irrigation, industry and town (domestic use); the unit production and delivery cost, which is presently unknown for all three types of water: groundwater, desalinated and recycled; the actual volumes of water in the water resources area of the country; and the problems in the water resource development and management and the technical and administrative aptitudes of the staff of the water managing organisations. The data collected about the whole of Saudi Arabia were obtained during my visit to MAW in Riyadh in November 1988. In Tihama Asir, rainfall data has been compiled, according to name and location, from rainfall stations lying within the catchment area of Wadi Jizan inside the Saudi Border, where data records are available from these stations. Hydrological data is presented, giving surface runoff values for Wadi Jizan as a whole and its subdivision among the five contributing wadis, namely Wadi Baysh, Wadi Dammad, Wadi Sabya, Wadi Haraba, Wadi Mishref. Values are given for infiltration rates at different locations of wadis and their catchment areas. Runoff coefficient values for Wadi Damad, and Wadi Jizan and the neighbouring wadis, any other information that may be useful in the estimation of wadis' surface water and seasonal and annual variations are presented. Groundwater data, an inventory of the observation wells in Wadi Jizan, Wadi Damad and Wadi Baysh, Wadi Amlah and Wadi Sabya present the following information:

- Location and date of construction.
- Diameter and drilled depth with well logging.
- The data on groundwater levels and its daily, seasonal and annual variations.
- Water quality and its area and time changes, aquifer characteristics, extent, depth, recharge, safe-yield, salt water wedges.

An inventory of existing drilled production wells in the area cover items such as location, date, depth, discharge and purpose.

The above data and information were obtained during a filed work visit to the study area of Tihama Asir in December 1988.

The research also involved intensive field work, counting reservoirs for all the cities in Tihama Asir, visiting the development project at Wadi Jizan to establish the water level in a well at the wadi there, and to see the distribution network to Tihama Asir's cities, such as Jizan, Sabya and Abu-Arish. Survey interviews were conducted with the authorities:

- in the city Municipality;
- in the Emarrat Jizan library;
- in the MAW library in Riyadh and Jeddah;
- with some of the farmers in the wadis.

The purpose of these interviews was to understand the water problems of the area.

The results of each survey are to be found in Chapters 3, 4, 5 and 6. Although much of the statistical information used in the study was collected from government institutions, this does not extend beyond 1988, in some cases, where available, more up-to-date information has been included.

As a basis for the work of improving the water use in Saudi Arabia, as much statistical data and direct observation as possible must be assembled. The more figures that are available, the more surely can future developments be gauged. Because of the break in the series of figures such as, for instance, the number of wells to supply water for industrial use, and agricultural irrigation, as well as likely future needs. This has been done by estimating water use and population growth in relation to water needs.

1.7 Plan of thesis

Chapter 1 introduces the study, identifies the problems under investigation and the methods used to explore the issues. It offers an overview of water resources and water use in the arid lands worldwide, in Saudi Arabia and in Tihama Asir.

As water resources are controlled by the physical geography and climate of a region,

Chapter 2 discusses the geological, geomorphic and climatic characteristics of Saudi Arabia and Tihama Asir. At the end of this chapter is a review of water supply, soils and natural vegetation.

Chapter 3 examines surface water resources in Saudi Arabia and Tihama Asir, and considers wadi floods, control of floods, and dams. Water pollution is also examined.

Chapter 4 examines groundwater in Saudi Arabia and Tihama Asir, identifying the deep aquifers (principal and secondary). Well development with respect to ground water movement and ground water pollution is also considered.

Chapter 5 examines artificial water supplies, and describes various processes used to desalinate seawater. The impact of the use of desalinated water and treated sewage in Saudi Arabia is considered: their utilisation, effectiveness and importance to Saudi Arabia's water supply.

Chapter 6 examines water use and demand in Saudi Arabia and Tihama Asir, and examines a number of irrigation methods and systems. The chapter also considers projected water demand in respect of the economic development of Saudi Arabia and population expansion. The water plans for several cities are discussed.

Chapter 7 attempts to bring together present and future water supply and demand in Saudi Arabia.

Trial water budgets for Saudi Arabia and Tihama Asir are proposed.

Chapter 8 attempts to identify some conclusions about water resources and use, and from these some recommended routes forwards for Sauid Arabia and Tihama Asir.

Chapter Two

General Background

Introduction

Saudi Arabia exhibits immense variations in topography, climate, hydrology, soils and vegetation. This chapter examines the principal geographical features of Saudi Arabia in general, and of the region of Tihama Asir in particular.

The examination, whilst providing a general background, focuses on features germane to the hydrology of the country and the region. Soil characteristics, which determine the rate of infiltration and thus affect the rate and amount of runoff, are examined in detail. Botanically, plants in Saudi Arabia exhibit xerophytic adaptations to carry them through the long rainless summer. Climate, the focus of hydological input, is examined in terms of air temperature, relative humidity, wind and rainfall. However, modifications to the ground layer of vegetative scrub influence runoff as it increases infiltration and evaporation. Therefore, vegetation reduces floodpeaks and controls soil erosion.

In any country where there has been a comparatively modest amount of earth science research, there are bound to be controversies. In the case of Saudi Arabia, it is only in recent decades with the development of the oil industry, the accelerated population growth and the resulting need for water, that serious geological work has taken place. Previously, the region was viewed only in the general formation of large-scale features.

Saudi Arabia is in a world zone which has undergone, in the recent geological past, and is still undergoing, large scale changes. These changes have produced, particularly in the mountain zone, an extremely complicated arrangement of outcrops, resulting in many features which still lack satisfactory explanation. The dominant feature, apart from the sand dunes of the desert foreland, is the mountain wadi. This appears as a generally deeply-cut dry valley, that experiences only occasional flow. The wadi forms part of a drainage system etched on what is predominantly a limestone highland, where the wadi is wide; and on an ophiolite highland, where it is narrow, except where a wadi occupies a fault-line. This brings into consideration past pluvial and drier periods, together with sea level changes. The relationship between the cutting of wadis, the formation of their extensive alluvial fans and the presence of obvious erosion surfaces, await detailed investigation. Of particular significance for water research, is the development of the alluvial terraces. Wadi terraces of gravels provide a particularly suitable aquifer and knowledge of their chronology and formation sequence would be an asset in attempting to locate preferred flow routes. However, there is still controversy about the basic factors concerning the environment in which the gravels were laid and in which they were subsequently dissected. The higher rainfall of a more temperate period might be thought to be the obvious cause of erosion, but it would also result in a more luxuriant vegetation and greater soil development, with the result that flows might be diminished and therefore there would be less erosion.

Geology is directly related to surface and groundwater by governing its flow, residence and quality. The geology is discussed in this chapter with the various rock types, their continuous or dislocated vertical and horizontal extent, the transmissivity governing both water movement and quality and also the storage capacity.

The section on topography contributes to the clear perception of the physical setting of the water resources. In particular the sand dunes of the desert foreland, emphasised in the present study for being important fresh water-bearing features of noticeable groundwater recharge value, have either been ignored or underestimated by previous studies.

Soils are discussed in as much as they are a medium of recharge. Hence the zonal or geologic soils are given more attention than the agricultural or biological soils, with the interest in either case being in the effect of salinity on the infiltrating recharge water as determined from chemical analyses of soil samples collected and analysed by the present study. Climate, the discussion on the state of the meteorological sites belonging to the various organisations, aims at portraying the actual level of efficiency of managing this sector of climatic observation vital to water resources.

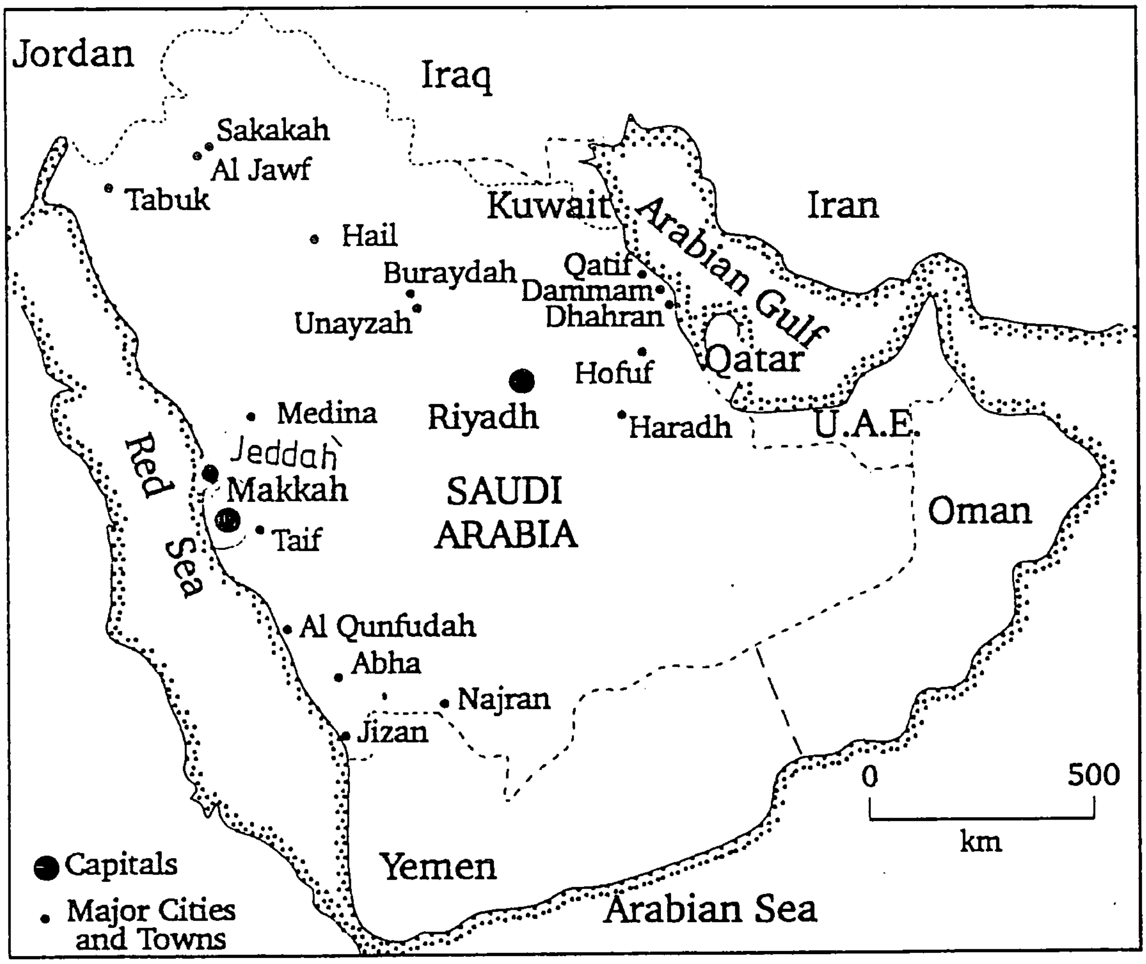
2.1 Area

Saudi Arabia is a quadrangular peninsula, lying between the Arabian Gulf, Qatar and the United Arab Emirates to the east; the Red Sea to the west; Oman and Yemen to the south; and Iraq, Jordan and Kuwait to the north. It has a longitudinal extension of about 2400 km and a width of about 8800 km.

Saudi Arabia is one of the largest and most arid countries in the Middle East, covering an area of 2,250,000 km^2, almost ten times the size of Great Britain, and comparable to the size of the United States east of the Mississippi. It occupies approximately four-fifths of the Arabian Peninsula (Figure 2.1).

Saudi Arabia is situated between longitude 35°E and 56°E, and between latitude 16°N and 36°N. The coastline measures 1760 km along the Red Sea and 560 km along the Arabian Gulf (Al-Sharif, 1977).

Figure 2.1: The Kingdom of Saudi Arabia



Source; M.A.W

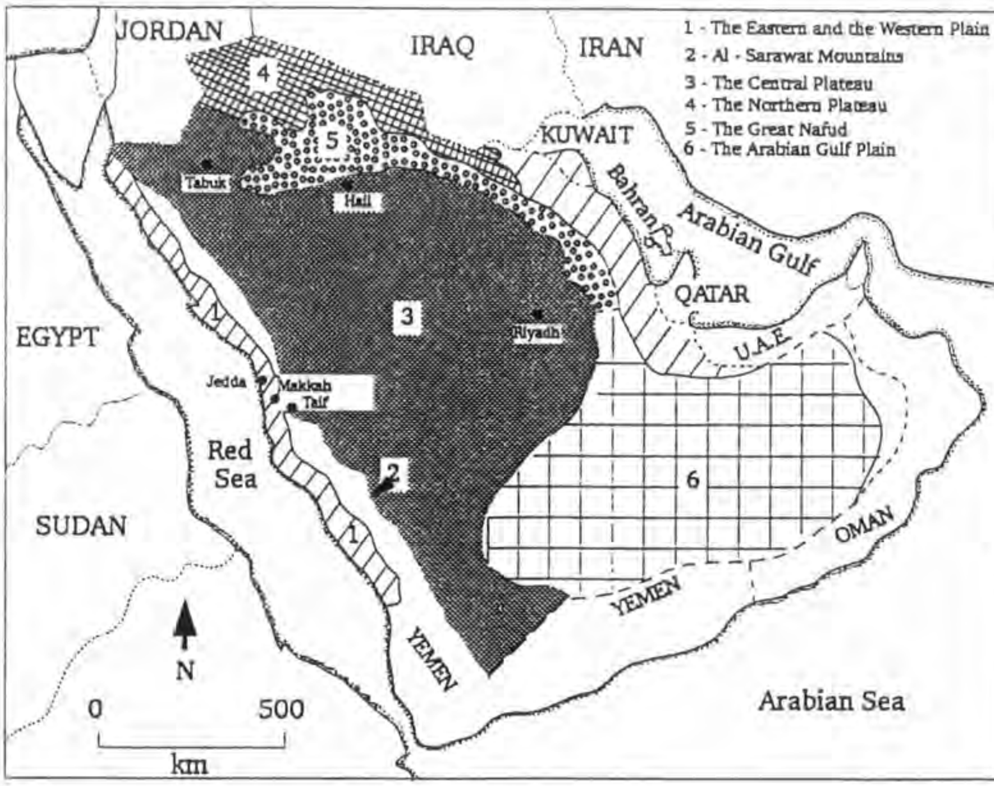
2.2 Topographical zones in Saudi Arabia

Saudi Arabia can be subdivided into six zones, each with a characteristic topography: central, south-western, western, northern, eastern and south-eastern (Rub-al-Khali). These six topographical zones are shown in Figure 2.2.

The central zone is considered the heart of the country, and covers an area of 20,000 km^2. The capital, Riyadh, is located in this zone. The plateau Najd slopes towards the east from an elevation of about 1,000m in the west to between 600 and 800m at its easternmost limit. The heart of this zone is the area of Jabal Tuwaig. The most important oases are Buraidah, Unaizah, Al-Kharj and Al-Aflaj. Nomadism has been a traditional feature of the zone, although, with the advent of oil wealth the Bedouin have been drawn increasingly to the city. The south-western zone, covering an area of 2,020 km^2, is a relatively fertile area with coastal mountains in the extreme south west. Mountain peaks rise to 10,000 m. Abha, Jizan and Najran are the major cities. Most of the Asir region, which starts where the Tihama narrows south of latitude 20°N stands above 1,500m, and some peaks top 3,000m. The government recognises the region's agricultural potential and has undertaken irrigation schemes in the Wadi Jizan and Abha areas.

The western zone, covering an area of 18,000 km^2, includes the coastal plains bordering the Red Sea and Hijaz mountain. This zone contains the holy cities for Muslims of Makkah and Medina, the business centre and chief port of Jeddah and the summer capital Al-Taif. The mountains in Southern Hijaz reach heights of up to 3,000m, with a northern plateau of 1,000-1,500m. In the west they fall steeply to a narrow coastal plain. The eastern side of the Hijaz mountains is less precipitous, and despite the scarcity of water is better suited to agriculture. This area is ideal for oasis settlements as it is the obvious route for caravans that have passed from north to south for millenia (Abu-Alainine, 1979; Al-Sharif, 1977).

Figure 2.2: Topographical zones of Saudi Arabia



In the northern zone, Hail, Tabuk, Sakaka and Al-Jouff are the main towns. This zone is suitable for arable farming and animal husbandry. The zone comprises the area lying to the north of Al-Nafud Al-Kabir, and extends to the Jordan-Iraq borders. The topography mainly consists of small hills standing on a wide plateau which is dissected by innumerable valleys which trend east-north-east. In the extreme north-west of this zone there is a depression, possibly formed by tectonic movements, now occupied by Wadi Al-Sarhan. Eastward from this depression, there is an extensive basalt flow of recent age extending into Jordan, known as Al-Harrah. Al-Harrah has an elevation of 300m above the bottom of Wadi Al-Sarhan. The wadi plateau, which is known as Al-Hammad, lies mainly to the east of Al-Harrah and has a gravel cover. The elevation of this zone is from 1000m in Al-Harrah to about 400m in the extreme eastern part of the plateau.

The eastern coastal zone, covering an area of 500 km^2, is located between the Musandam peninsula of Oman and Shatt-al-Arab which links Iran with Iraq and Kuwait. It is not higher than 200m. It consists mainly of an undulating plain with occasional low hills. Much of the surface is covered with sand and gravel. Other areas are characterised by gravel plains and dry wadis. The coastal waters are mostly shallow with coral reefs. Another prominent feature are the salt marshes (sabkha) which are formed by the sea or by evaporated underground water. As this area is much lower than the rest of Saudi Arabia it supplies a lot of water for agriculture in the Al-Hasa and Al-Qatif oasis, two of the largest oases in the Arabian Peninsula. This zone is the country's wealthiest, containing massive petroleum reserves (Al-Sharif, 1977; Fares and Yusef, 1976)..

The south-eastern zone of Saudi Arabia is completely occupied by Rub-al-Khali. This is a sand ocean with neither permanent grazing nor nomadic agriculture due to the absence of water. It is one of the largest sand deserts in the world, and covers an area in excess of 500,000 km^2. The zone is bounded by Gulf of Aqaba to the north and Yemen to the south. Its highest elevation is 2,750 m. Although there is no permanent habitation, the area is crossed by caravan routes. There are no oases, although several wadi systems drain into the zone (Al-Sharif, 1977; Fayed, 1976).

As an alternative means of classifying the land surface of Saudi Arabia, similar types of relief and climatic regime in different parts of the country can be examined under topographically specific headings.

2.2.1 The eastern and western coastal plains

The coastal areas are located in the east along the Arabian Gulf and in the west along the Red Sea and they are characteristically flat. The Arabian Gulf is a broad, shallow epicontinental sea with a maximum depth of 110 m. The shore is irregular, low, sandy and the water has many shoals so that changes in tide and wind direction cause the water front to shift backwards and forwards by several kilometres. Consequently, the low coastal flats are covered by the sea periodically. The elevation of the Arabian Gulf coastal region rises gradually inland at a rate of about one metre/km.

Along the north-western shore of the Arabian Gulf, from al-Jubayl northwards to Kuwait, are low rolling plains covered with a thin mantle of sand. The roots of bushes and grass hold the sand in hummocks and form an irregular, bumpy terrain called dik'akah. South of Al-Jubayl is a wide belt of drifting sand and large dunes which widens southward, and beyond Al-Hafuf merges with the sand area known as Al-Jafurah. These parts of the Arabian Gulf coastal region are not covered with sand or sabkha but are barren rock terrain developed from Eocene, Miocene and Pliocene limestones. In the fertile oases there are many wells and artesian springs with abundant fresh water, which makes these two areas important producers of dates and other agricultural products.

The Tihama, at the southern tip of the western Red Sea coastal plain, is characterised by numerous short wadis which offer a combination of climate, soil and water suitable for crop and livestock production. The Tihama is bounded inland by the scarp mountains and towards the sea by the shelf area. Although very narrow in the north, it widens irregularly towards the south and attains a maximum width of 40 km near Jizan. The western portion of the Tihama consists of depositional surfaces, about 3 m above sea level. This grades upwards into the higher eastern Tihama which is largely a pediment cut on crystalline and Tertiary rocks and covered with alluvium, sand and gravels. The pediment was cut after the last fault movement along the front of the scarp mountains. In the area 175 km northwest of Jizan, basaltic lava flows and cinder cones rest over the fault area and on the adjacent coastal plain. Numerous drowned tributaries, reaching depths of 50 m below sea level, cut through the seaward edge of the coastal plain extend out onto the shelf. At and near the coast north of Jeddah are the remnants of a 20 m raised surface. From Um Lejj northward to the Gulf of Al-Aqabah are other raised surfaces of elevations of 6, 10, 20 and 30 m above sea level. These four elevated surfaces are on coralline rocks and have resulted from vertical movements along northwest-south faults (Al-Sharif, 1977).

2.2.2.The highlands

The highlands stretch along the Red Sea with a partial gap in the vicinity of Makkah. The western highlands extend nearly 1,600 km from the Gulf of Aqaba to Aden in the southwest. The highlands have a plateau which ranges between 300 and 600 m elevation in the north, and they become higher and more rugged to the south at Medina, where they reach a height of 2,400 m south of Makkah. The mountains are developed on folded and faulted Precambrian rocks, and many of the ridges and wadis mirror these structures. Between Jizan and Al-Taif they parallel the escarpment, occupying grabens and the crests of anticlines. From Al-Taif and Makkah northward, the height and ruggedness of the mountains decrease appreciably but the width of the belt increases to a maximum northwest of Medinah (Al-Sharif, 1977).

The height of the mountains in Asir and their proximity to the monsoons of the Indian Ocean brings to this area the highest rainfall in the country. There are several peaks in the southwest, the highest of which is over 2,750 m and located south of Asir. The mountains slope gradually to the east in the central plateau.

2.2.3.The central plateau

Located east of the highlands, this region forms a moderate to high plateau with elevations ranging from 800 to 1800 m. It extends towards the interior desert plateau. The immense area of elevated terrain in west central Saudi Arabia is known as the central plateau region. This area is bounded from the east by the Nijed region, from the north by the great Nefud and from the west by the mountains along the Red Sea coast and from the south by Yemen. It has a trapezoidal shape and a width of 500-600 km, and is geographically one of the largest provinces in Saudi Arabia. The topography of the central plateau region was formed on an ancient land mass, peneplaned probably in Precambrian times, then during later times elevated as a great plateau and tilted gently northeastward. The high western edge now forms the crest of the coastal mountains and marks the continental division between eastward and westward drainage (Al-Sharif, 1977; Rajab, 1978).

In general, the central plateau region has a gradual northeastward slope on which many drainage systems have developed. The largest of these is Wadi Al-Rimah, the extension of which, Al-Batin, carries its drainage all the way from its source east of Al-Madinah to the Arabia Gulf basin near Basrah and Tathlith which joins from Wadi Ad Dawasir.

2.2.4 As Summan Plateau

The As Summan Plateau borders the eastern zone from the west. It is a hard rock plain 80 to 250 km wide and is fairly flat. The elevation averages about 250 m and its western margin adjoins Al-Dahna sands. Some vegetation grows in sandy depressions which form a major grazing area in winter and spring.

As Summan Plateau is actually part of the larger Syrian Plateau to the north. The whole physiographical unit extends from a point about 300 km south of Al-Hafuf northwestward across northeastern Saudi Arabia and western Iraq and into Syria against the Trans-Jordan Highlands. There it attains its maximum width of 650 km. In Iraq, Syria and northern Saudi Arabia the plateau is a vast desert of gravel and rock plains underlain by Cretaceous and Tertiary sedimentary rocks near the junction of the borders of Saudi Arabia, Jordan and Iraq. The plateau attains an elevation of nearly 900 m and forms an important drainage divide. On the eastern side of this divide a well co-ordinated system of dendritic wadis, such as Al-Widyan, carries drainage eastward onto the plains of Iraq into the Euphrates River. On the western side, drainage flows into Wadi As-Sirhan, a great depression over 300 km long, 30-50 km wide and 300 m below the plateau surface (Al-Sharif, 1977; Rajab, 1978).

2.2.5 Najd plateau and the escarpment region

The escarpment region lies to the west of Al-Dahna plateau. It is nearly 320 km wide and is dominated by several steep escarpments with a gentle eastern slope. The average elevation of the region is between 300 and 1,000 m and allows more grazing than other areas.

The Tuwayq, west of Al-Riyadh, is the largest area, 800 km in length, with average elevation above sea level of 840 m and maximum of 1500 m. The top is capped by upper Jurassic limestone and it rises about 240 m above the plains to the west.

Al-Armah, northeast of Al-Riyadh, is approximately 250 km long with an elevation of 540 m above sea level. It is less conspicuous than the Tuwayq because it stands only 120 m above the plain to the west. Al-Armah is topped by upper Cretaceous limestone.

In general, resistant limestone in the summits of Najed region, and less resistant rocks, mainly sandstone, underlie the intervening plains. Where soluble strata like anhydrite and gypsum were formerly present, their removal by solution is marked by large sink holes and solution cavities at the base of the scarps. The tops of the cuestas are not true deep slopes, the limestone beds are truncated at very low angles by erosion surfaces sloping eastward towards the sandstone plains (Al-Sharif, 1977). The region is transected by a number of major wadi channels. Examples of such channels are Wadis Al-Hinwi, Al-Dawasir, Birk and Nisah. This gives rise to an interesting geomorphic problem. The drainage along these is west to east and it has been assumed that they were cut by eastward flowing streams. However, although they are actually deep canyons throughout most of the cuesta, they are much wider at their western ends where they form V-shaped notches in the escarpment face. The desert streams, many completely dry at the surface, flow in wadis from the higher plateau areas to the west and enter the basins. Here they either appear as springs or cross the basins and become lost in the desert sands. Other smaller streams flow down the steep slopes of the escarpments and contribute additional water to the basins.

2.2.6 Great Sands Area

The Great Sands Area Consists of the following three main deserts:

(1) The Great Nafud, in the north, covers approximately 57,000 sq. km. It lies in northwestern Saudi Arabia between Hail and Al-Jawf, and is shaped like a giant hand with long fingers pointing westward. It occupies a broad basin of low relief: Al-Jawf-Sakakah basin. To the east and north in the Syrian Plateau and to the west and north the Hisma Plateau and Jabal Shammar, respectively. The Great

Nefud has reddish sand and rolling dunes supporting sparse vegetation. It is a region with neither streams nor oases.

(2) Rub-al-Khali, in the south, is approximately 1,200 km long and has a maximum width of nearly 640 km, covering an area of about 647,500 sq. km, making it the largest continuous body of sand in the world. The sand is of red-orange colour and medium to fine grain like that of the Great Nefud and Al-Dahna. In the eastern part of Rub-al-Khali is an enormous group of sabkhas interspersed among the sand dunes. By far, the largest is Um As Samim with a length of over 100 km. Most of Rub-al-Khali is uninhabited except for some Bedouins who move into the fringe areas during rains to take advantage of the pasture or others who frequently move in such places as the northwest where water wells are common.

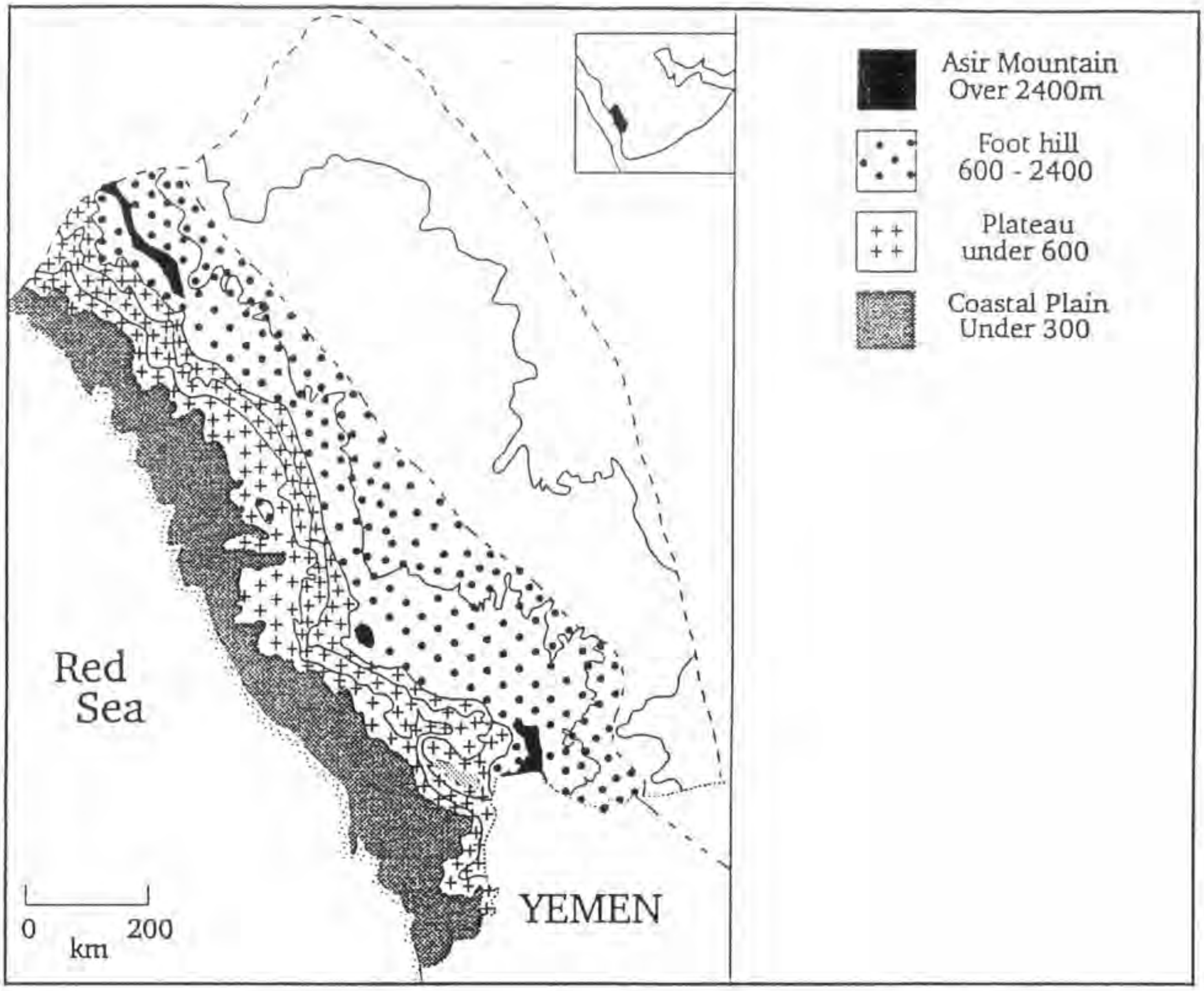
(3) Al-Dahna plateau is a long and narrow sand belt which extends approximately 1,300 km from the great Nefud in the north and Rub-al-Khali in the south. It is one of the most distinctive physiographic features of Saudi Arabia. It lies between As-Summan Plateau on the east and Najed Plateau in the west. The sands of Al-Dahna are bright red-orange due to a coating of iron dioxide on the quartz grains. Although water is scarce, Al-Dahna is a favourite grazing ground for camels in the winter and spring (Al-Sharif, 1977; Rajab, 1978).

2.2.7 Topography of Tihama Asir

Tihama Asir is that narrow coastal strip of land along the Red Sea which extends from the frontiers of the Yemen in the south up to 50 km and 170 km north of Biuk Plateau of Wadi Itwad, with a width of about 30 km from the rift of Asir Mountains to the Red Sea.

The area consists of three distinct topographic regions which show different hydrological characteristics (Figure 2.3):

Figure 2.3: Topography of Tihama Asir



(1) The Asir Mountain range rises abruptly to an altitude of over 3000 m. from the plain, and extends north-south parallel to the Red Sea. The range, which lies to the east of the study area, delineates the border between Saudi Arabia and Yemen, from the emirates of At Tuwal in the south, to Beni Malek in the north. Beyond, they form the limits between the Jizan region and the Najran and Asir regions. The mountains are cut by deep wadis, meandering towards the coastal plain, which provides communications within the mountains. The major valleys are connected with the provinces of the hinterland. Nearly 80% of the catchment of Wadi Bishah is located in this area.

(2) The foothills area bordering the eastern side is covered mostly with boulders, rocks and depressions which are largely filled with alluvial materials having good water holding capacity. The land is gently sloping and partly plateau. Vegetation is sparse, but shrubs will survive if not cut for firewood too often. Tributaries of Wadi Bishah and Wadi Sabya which originate in the Asir mountains cross the foothills to the coastal plain. This area is about 150 km long and 10 km wide.

(3) The coastal plain lies between the saline land (sabkhas) along the Red Sea coast and the foothills, an area about 100 km by 20 km, where along the wadis, the main agricultural development is taking place. Lands irrigated by floods extend along the wadi courses. These are usually flash flooded with water flowing down at irregular intervals from the Asir Mountains. The soils are alluvial and mainly of good water-holding capacity, free from stones and rocks (Abu-Alainine, 1979; Al-Sharif, 1977).

The plain varies in width from 15 to 60 km and is bounded on the east by a massive rugged mountainous wall of igneous and metamorphic rocks which is over 400 m above the Red Sea. The plain is interrupted at the southern extremity by mountains.

The coast is sealed off from deep water by a continuous coral reef that severely restricts the establishment and development of ports, such as Jizan Port. The occasional heavy rain storms, coupled with the steepness of the sloping mountains, cause violent floods in the wadis. This plain slopes gently from the mountain foothills towards the sea and is marked every 10 to 20 km by a major wadi bed following the slope. The coastal plain includes inland saline flats made up of silt, clay and mud termed 'sabkah'.

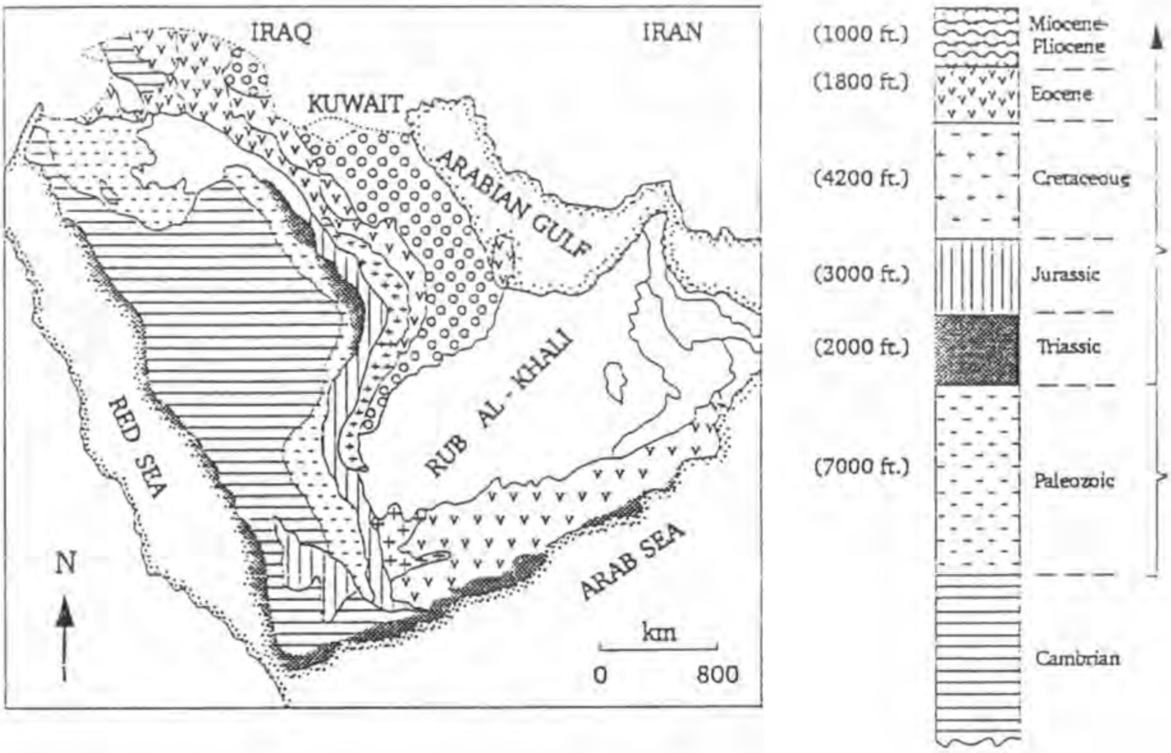
2.3 Geology

2.3.1 The Geological History of the Arabian Peninsula

The Arabian Peninsula is a huge crustal plate composed of ancient sedimentary and volcanic rocks. Figure 2.4 shows the geology of Saudi Arabia which can be divided into six regions. In Precambrian times the peninsula was attached to Africa as part of the African shield. In the late Precambrian its surface was deeply eroded and peneplaned.

At the beginning of the Cambrian, a great sedimentary basin or geosyncline (the Tethys) had developed north and east of Arabia in the area now occupied by Turkey, northern Iraq and northern Iran. Throughout Palaeozoic, Mesozoic and early Cenozoic times many thousands of metres of sediments accumulated in this deep, slowly sinking trough. Between the Tethys and the Arabian Peninsula lay broad epicontinental seas. These spread widely over the eastern parts of the peninsula, depositing on it a relatively thin succession of almost flat-lying, Palaeozoic, Mesozoic, and early Cenozoic strata. Inland of the shoreline, continental sediments were laid down. From time to time, in response to slight vertical movements, the shoreline moved back and forth across parts of the peninsula, halting the deposition of sediments in places, and thus producing unconformities.

Figure 2.4: The geological surface of the Arabian Peninsula



In the late Cretaceous, orogenic movements all the way from Gibraltar to the Island Arcs of the Pacific Coast heralded the destruction of the ancient Tethys. The thick sequence of marine strata in the geosyncline was buckled into great folds and sliced by great overthrusts. This deformation constituted the first stage of the Alpine orogeny which was to give rise to the Alpine-Himalayan mountain chain. The second stage began in the late Tertiary when the deformed rocks of the geosyncline started to rise. The Arabian Peninsula itself was little affected by this uplift except for being tilted slightly toward the eastern Arabian Gulf region where sinking and sedimentation continued. This second stage of the orogeny culminated in the formation of the Taurus, Zagros and Oman mountains (Abu-Alaulae, Noury, 1983).

In the middle Tertiary the Arabian tectonic plate split away from the African shield along the Red Sea trough. The plate then began moving slowly northeastward, impinging on the edge of the great Asian tectonic plate in Iran and perhaps even sliding beneath the latter. This separation of Arabia from Africa was accompanied by extensive volcanism along the western edge of the peninsula. Throughout the Palaeozoic and Mesozoic, and even during the Tertiary orogeny, the cover of shelf sediments was barely disturbed.

The Arabian peninsula can be divided geologically into two structural provinces. A western province, known as the Arabian Shield, is part of the Precambrian crust, and is generally exposed but locally covered by Tertiary volcanic rocks. An eastern province, called the Arabian Shelf, consists of a thick sedimentary covering of the Arabian tectonic plate. These two provinces are shown in Figure 2.4.

(1) The Arabian Shield is bounded by a 2,000 km straight edge along the eastern shore of the Red Sea, and the 1,500 km long northern shore of the Arabian Sea and extends inland as much as 700 km to form the great Najd towards Riyadh and to form a lesser plateau 300 km wide in Yemen Arab Republic. It may be considered as having two components as described below.

The Western Arabian Shield, which forms Central Najd, Hijaz and Asir and is composed of Precambrian plutonic, magmatic and metamorphic rocks, with some Tertiary plateau basalts. It has been essentially a stable craton since Cambrian times. The Southern Arabian Shield, outcrops of which extend along the northern shores of the Arabian Sea and which has also been essentially stable since Cambrian times.

(2) The Arabian Shelf is of sedimentary origin and has a cover of rock ranging in age from Cambrian to recent times. It comprises all sedimentary rocks lying on the northern and eastern flanks of the crystalline basement, which had been eroded and peneplaned in the Lyalian interval of time separating the Pre-Cambrian from the Cambrian. Facies were essentially torrential, littoral, lagoonal and shallow marine. The position of the coastline changed as the main shield rose and fell in slow pulsations. Minor downbeats permitted small ingressions of the sea whilst major descents resulted in great marine transgressions. As the surface of the shield was relatively level, small changes in elevation of the land or the sea resulted in great lateral displacements of the coastlines.

Based on their structural attitude, sediments of the Arabian Shelf may be considered as lying in two different regions as follows:

(1) The Interior Homocline, where the sediments are essentially under formed falling gently off the crystalline basement. Due to the location of basement and its swells or arches, the gentle dips nevertheless result in a wide synclinarum on the north towards Wadi Sirhan in a broad anticlinorum based on the Hail and Central Arabian Arches, and on another gentle synclinorum of the Rub-al-Khali which lies between the western and southern shield segments.

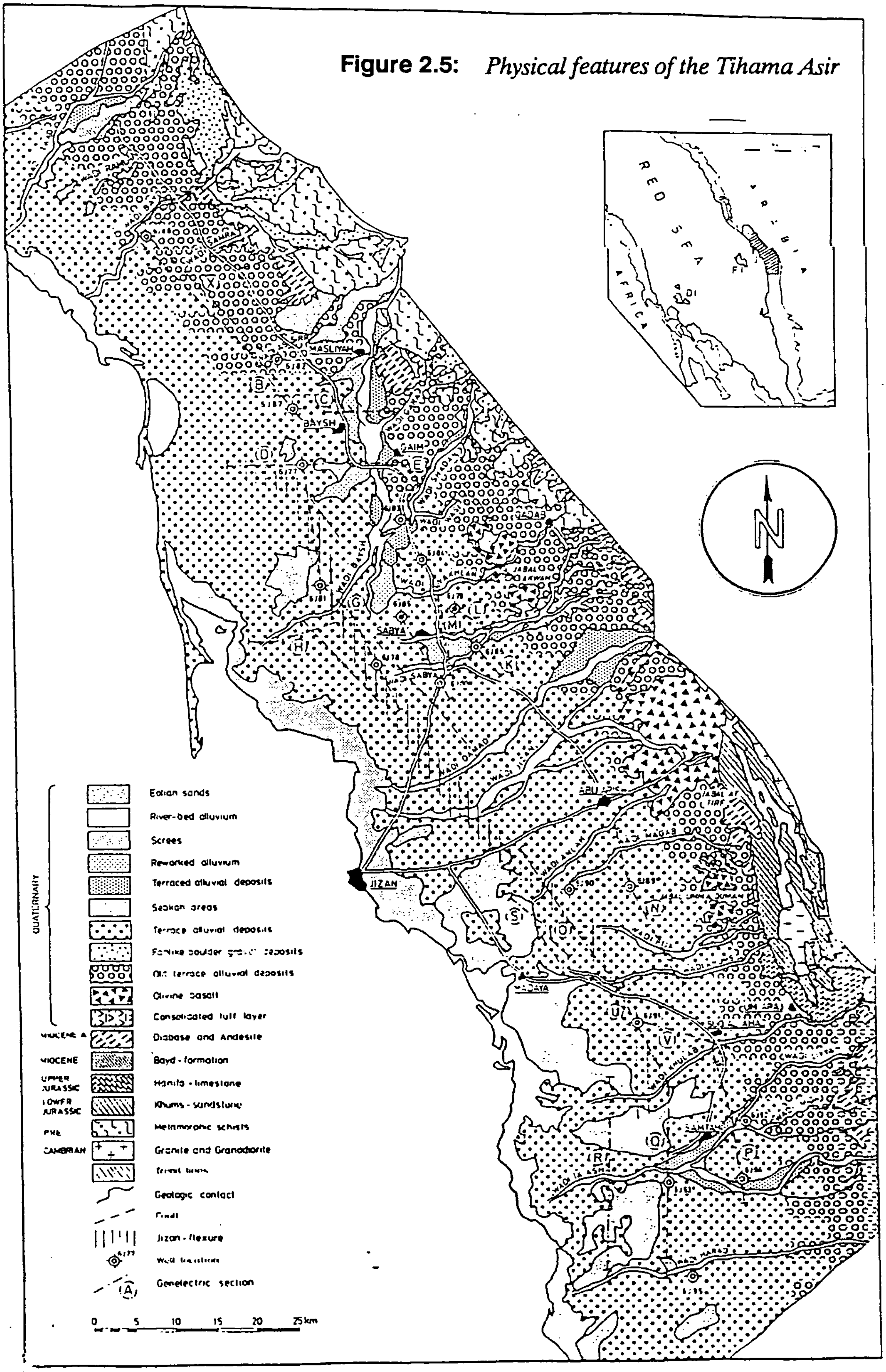
(2) The Basins, where the basement has sunk and into which abnormally thick sedimentary beds have been deposited. They include the Rub-al-Khali (Tertiary), the Northern Arabian Gulf, the Dibdiba (Cretaceous) and the Sirhan-Taraif (upper Cretaceous) and ocean Basins. From the Cambrian period onwards, a succession of nearly flat-lying strata were laid down over the eastern two-thirds of the peninsula at time when what is now the Arabian Gulf was of much greater size. These sedimentary strata of which the great plateaux of central and eastern Saudi Arabia are formed tipped and now gently slope away to the north-west, east and south-east. They are now exposed in land running roughly north and south because of ancient sinking of the Arabian Gulf area, and deformation of the rock structure. Differences in their resistance to erosion led to the developments of escarpments such as Tuwayq Mountain west of Riyadh. From the borders of Iraq and the Arabian Gulf, plateaux rise westwards in benches across the great sedimentary basin extending from the north of the country to its termination in the vast desert depression on Rub-al-Khali in the south. The northerly portion of the basin contains the Great Nefud desert from which two areas stretching southward embrace Riyadh and part of the high ground west of the city (Rajab, 1978).

2.3.2 Geological Features in Tihama Asir

The Tihama Asir belongs to the eastern margin of the Red Sea rift wadi. Its evolution started in the Oligocene and continued into recent geological times. The geological history of the area, however, began a long time before the development of the recent tectonic pattern with the deposition of Precambrian eugeosynclinal sedimentary and volcanic rocks. These series, metamorphosed and heavily denuded from the truncated upland of the present Arabian Nubian Shield complex, had been affected by several Precambrian orogenic and plutonic events before the cartonisation occurred. The Precambrian series are exposed all along the northeastern flank of the Red Sea. Many volcanic intrusions, dyke swarms and flows which occurred during the development of the Red Sea rift are characteristic of the Jizan Plain. Several small volcanic cinder cones, which are still in a good state of preservation, confirm that volcanic activity has continued to recent geological times (Figure 2.5). The Tihama Asir component in the down-faulted graben block of the Red Sea, has a mantle of Tertiary and Quaternary sediments thickening towards the coast and also some small basalt flows. The uplift has resulted in steep escarpment facies down which torrents rush in deep wadis and then flow more slowly across the coastal plain, but frequently fail to reach the sea.

Palaeozoic and Mesozoic sediments occur as capping to the basement, but in some places they are preserved in down-faulted beds. In the study area only a few remnants on the ancient cover remain on the basement of it. These include the Wajid Sandstone of Jurassic age, and the Khums and Hanifah formations which are found in the upper reaches of Wadi Khums and Wadi Khulab. Tihama Asir fronts upon a pronouncedly flat coast, broken only by the slight 50 m elevation of the Jizan salt diapir. The area immediately adjacent to the coast is taken up by a sabkhah zone, virtually as long as the coast, and with a width up to several kilometres. Beneath the ground surface are

Figure 2.5: *Physical features of the Tihama Asir*



alternate layers of silty, clayey sediments and evaporation products with a high salt content owing to the high groundwater level and the high rate of evaporation.

The sabkhah area must have been largely flooded at high-water and may be the transgression surface, or else it may mark a short period of advancement of the sea. The sabkhah area of the wadis gradually follows a slight but distinct rise between the wadis, and can be traced in the alluvial accumulation plain of the middle terrace.

Tertiary formations occur under much of the coastal plain and tend to outcrop in the foothills. They include: clay and marls locally associated with evaporites, zoogene limestone, detriti sediment of continental origin such as sand and gravel and basalts.

Alluvium occurs in the wadi beds and also as extensive sheets covering much of the coastal plain, so that the only alluvium remaining on the shield is in the wadis. The alluvial layers are thin, up to 12 m only. Results of studies of this alluvial material appear to indicate that before the present period of dry climate there was at least one humid period during which the rivers carried pebbles and a high proportion of large boulders over long distances.

The Tihama coastal plain in the vicinity of Jizan is situated in a geological depression extending from the sea to the foot of the Asir mountains. The promontory of Jizan is located on a salt dome, creating an elevation with respect to the coastal plain. The upthrust of the dome has deformed the overlying strata, creating an uneven terrain of anhydrite and gypsum hills on the east and west sides of the promontory.

In the fault zone in the eastern part of Jizan, the weakness in the batholith and the ring dyke of gabbro has been filled by volcanic ashes. The plain is completely covered with sedimentary sand and silt. Because of the sensitivity of these rocks in the western part of Jizan to contact with tidal water, many holes have been created in the steep faults which are found on the ground surface at the northeastern side of the promontory. The upthrust of the dome has resulted in the creation of uneven terrain on the east and west sides of the promontory. The most serious manifestation of the geological condition of the city (Jizan) is a large number of houses which are damaged by local subsidence or uneven settlement. The salt content in the coastal flats is so high that the corrosivity of these salts badly affects the life of the concrete structures and the steel pipelines used for water supply (Abu-Alaulae, Noury, 1983).

2.4 Soils

The aridity, high temperatures and the unstable nature (because of continued wind action) of the deposits have led to the mechanical disintegration or desert material.

Soils of the arid environment can be divided into two groups: soils of deflation and soils of deposition. The former are soils from which the finer material has been blown away to other locations, such as the soils of the catchment areas and the carbonate anticlinal ridges of the gravel plains on either side of the highland. The soils that have been deposited by wind and running water form the aeolian and fluviatile soils of the vast desert foreland of Saudi Arabia. Soils deposited by wind include the sands of the dunes of all forms and sizes, and also the veneer which covers the areas and wadi courses that reach out to the desert foreland from the mountains; those deposited by running water include the equally dominant desert foreland feature, the sabkhas. The sands of the dunes are highly permeable and demonstrate the highest infiltration rates of any soil type in Saudi Arabia (Al-Sharif, 1977; Abu-Alaulae).

Soils are discussed in the present study with regard to their mechanical and chemical composition, especially their porosity as governed by their content of coarse material and salt, and the effect these have on groundwater during recharge or residence. Interest is focused on a zonal soils rather than those under cultivation although some reference is given to the increasing salinity in the latter soils caused by a few seasons of cultivation. Salts accumulated in cultivated soils are eventually leached down by both rain and irrigation water into the groundwater (Al-Sharif, 1977).

Recharge takes place through all kinds of soil, whether natural recharge from direct rainfall over all the terrains, or from surface runoff limited to wadi channels, their outwash fans or the open Piedmont plain in parent deposits, or these two methods of recharge plus irrigation water return through reclaimed and cultivated soil, the factor of salinity of these soils as a medium through which recharge is taking place, is important and should be taken seriously in the existing situation of depleting groundwater resources. Hence the discussion of this physical aspect directly relates to water (Al-Sharif, 1977).

Soils consist of unconsolidated aggregates of rock and mineral fragments, decaying organic matter, living organisms and soil water. These constituents are in a complex, dynamic relationship with each other. Soil material varies in size from large stones and gravel, through grains of sand, to minute particles of silt and clay.

The properties of a soil depend on the composition of the parent materials, in particular the local bedrock; the climate in which the soil accumulated and weathered; any associated plant and animal life; the length of time the soil-forming processes have acted on the soil material; and the slope of the ground. The rate of physical breakdown is accelerated by changes in temperature, by wind and by floods. The soil constituents may have been transported to the region by the action of wind or water. Sometimes soils themselves are transported, such as the loess found in China (Al-Shalash, 1985; Al-Sharif, 1977).

Soil properties have much to do with suitability for uses. The rigidity and supporting power is of relevance to water course and dam construction; drainage and moisture storage capacity are relevant to the value of an aquifer; ease of penetration by roots is of relevance to run-off rates; retention of plant material nutrients is of relevance to agricultural use. Each of these factors is intimately connected with the physical condition of the soil. Soils transmit water and air to a greater or lesser degree. Permeability estimates indicate the rate of downward movement of water when the soil is saturated. They are based on soil characteristics observed in the field, particularly structure, porosity and texture. Permeability is considered in the design of soil drainage systems, in determining irrigation rates, and in construction where the rate of water movement under saturated conditions affects soil behaviour.

Local climate affects the type of soil, both directly by means of its weathering effects, and indirectly as a result of the vegetation cover for which climate is largely responsible. Different types of soil form in a hot, wet climate; a cold, tundra climate; under mid-latitude grasslands; and under coniferous forests. Soil can overlie, and be part-comprised of resistant rock such as granite or slate, less-resistant rock such as recent volcanic ash and lava, or sedimentaty rock such as sandstone, limestone and clay. The term rock is strictly applied not only to structures such as granite and limestone, but also to gravel, clay and unconsolidated sand (Knapp, 1983; Al-Sharif, 1977). As an example, on limestone, most soils are thin and dry, and on the steeper slopes soil may even be non-existent. However, where the residue can accumulate , retaining some of the lime content, a sweet, short turf, characterised by lime-loving plants, will develop. Several major soil types which develop on limestone are recognised, including red and brown soils on terra, and rendzino on chalk.

The size of particles affects the properties of soils in several ways. Water drains rapidly through open, sandy soils, but is retained in soils of very fine texture. In a clay soil, for instance, the particles are too small to allow adequate drainage. In some fine soils the water adheres so firmly to the particles as to restrict its availability to plants. Texture is perhaps the most important characteristic of soil and will be discussed first. Soil texture refers to the coarseness or fineness of the soil. Specifically, texture concerns the relative proportions of sand, silt and clay or the particle-sized groups smaller than gravel (less than 2mm in diameter). In many soils, gravel, stones and bedrock outcrop (Al-Sharif, 1977). A critically important property of soils is their control on the availability of water to plants and the ability of fine feeding roots to ramify within the soil. Infiltration is the flow of water from the ground surface down into the soil.

2.4.1 Soil Classification

Soils can be classiifed: features being selected logically on the basis of major soil properties, such as organic matter type, and by soil-forming factors such as climate. These can then be further divided according to similarity of soil properties until, at the fifth, sixth or seventh level, the units of classification have local significance in agriculture.

The resulting classification represents a chain of soils from the hot dry to the cool wet. The classification depends upon the balance between rainfall and evaporation. These are equally balanced in the Chernozem and those to the right are increasingly leached as rainfall becomes much greater than evaporation. The desert scrub in the arid soils giving away to short and then to lush, tall grasses as more water becomes available and then to broad leaved trees and finally coniferous forest as leaching becomes intense. This is at the surface in the arid soils and gradually appears lower down the profile, as the upward pull of evaporating water is diminished and leaching takes over.

The soils in the various areas of Saudi Arabia have been classified using the soil classification system adopted, that is defined in Soil Taxonomy. This taxonomy is used in classifying soil in many countries throughout the world. The system is based on clearly defined soil characteristics including morphological, physical, and chemical characteristics. Also included are soil temperature and soil moisture. There is a variety of soils resulting from variations between ten diagnostic surface or subsurface horizons which are recognised as being important to the classification of soils in Saudi Arabia (Figure 2.6) (MAW).

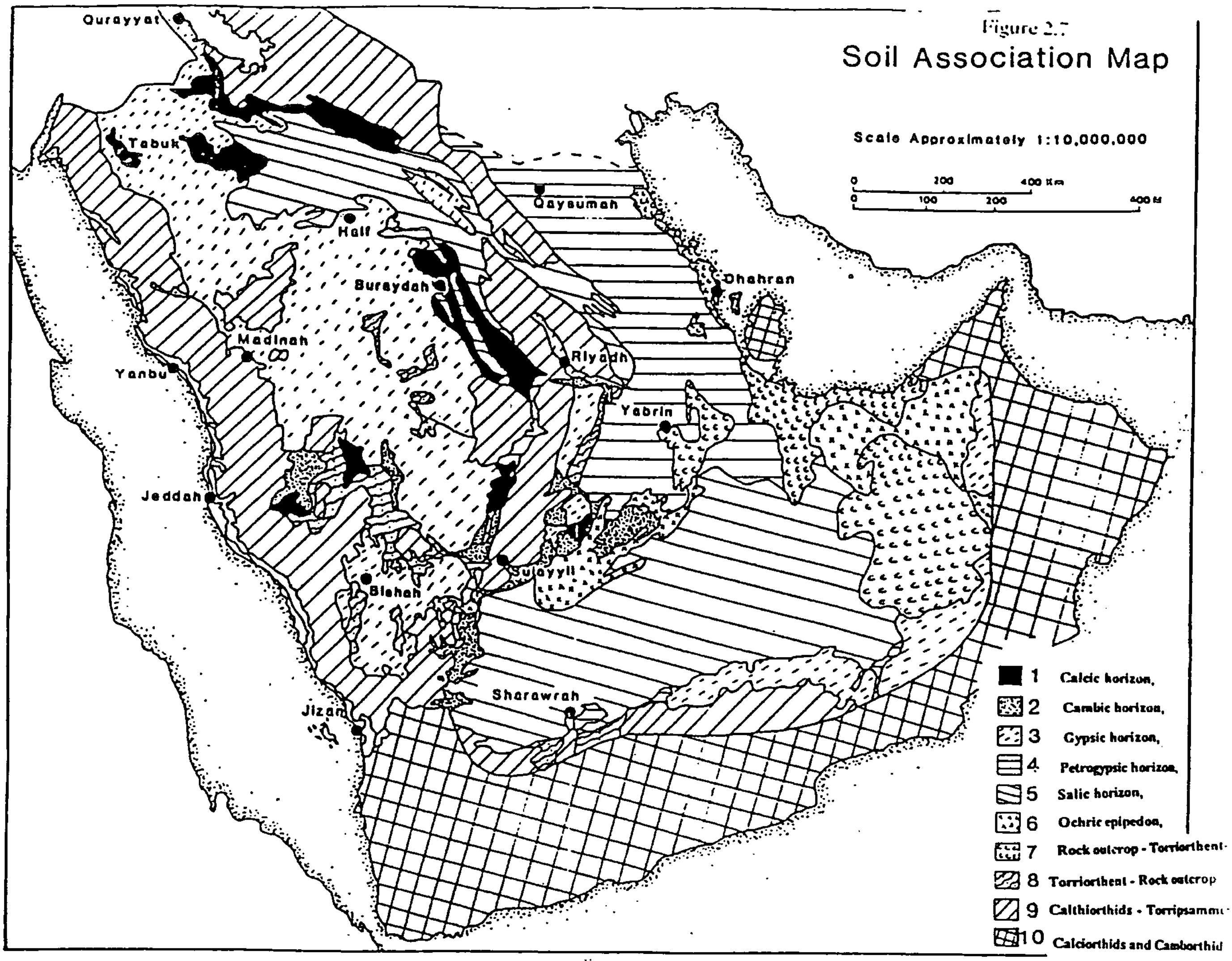
1. **Calcic horizon**, a subsurface horizon which has an accumulation of calcium carbonate or calcium and magnesium carbonate. Calciorthids and some Gypriorthids have a calcic horizon.

2. **Cambic horizon**, a subsurface horizon which has been altered to one or more of the following: redder or greyer colours; obliteration of rock structure and, in some soils, formation of soil structure; removal of most or all of the Carbonates, Camborthids, Eutrochrepts, and Haplaquepts have a cambic subsurface.

3. **Gypsic horizon**, a non-cemented or weakly cemented subsurface horizon enriched with secondary sulphates, Gypsiothids that do not have a pan have a gypsic horizon.

4. **Petrogypsic horizon**, a cemented subsurface horizon enriched and cemented with secondary sulphates. Gysiorthids that have a pan have a petrogypsic horizon.

Figure 2.6: Soil Associations in Saudi Arabia



5. **Salic horizon**, a subsurface horizon that has a secondary enrichment of salts more soluble in cold water than gypsum. Salorthids have a salic horizon.

6. **Ochric epipedon**, a light coloured subsurface horizon that is medium to low in organic matter. It is not as masssive or hard when dry. The major soils in Saudi Arabia have this kind of surface layer.

7. **Rock outcrop - Torriorthents**: found in mountains with slopes from 15-80 % of very shallow to shallow loamy-skeletal, non-saline to slightly saline soil. Permeability is moderately rapid. This type of soil is not suitable for irrigation due to its shallow depth to rocks, its rock outcrop and deep slopes at elevation between 500 - 27000 m respectively.

8. **Torriorthent - Rock outcrop - Torrifluvent.** This is a deep loamy soil found on foot slopes of hills and knolls and alluvial fans; slopes are generally between 0-5%. Permeability of this soil is moderate and salinity is nil to slight.

9. **Calthiorthids - Torripsamments**: sandy, deep soils with 0-3% slopes. Nearly level on smooth plains, and found on plains of old alluvium, characterised by low salinity to no salinity at all, moderately rapid permeability.

10. **Calciorthids and Camborthids - lavaflow**: this is a type of deep stony soil and lava rocks found on level and strongly sloping hills, footslopes and alluvial fans nearly level to strongly sloping areas of lava flow. Drainage nets are not well developed. Lava flow consists of thin deposits of extrusive rock and include jumbled mass of boulder sized rock and rocks broken into angular stones. This soil is not suitable for agriculture. Representative areas are found on the Red Sea coast.

Figure 2.6 shows ten soil samples from Saudi Arabia. The texture classification of soils throughout the country has in general studied loam soils. In examining soil particle size distribution, sand ranks top with an average of 77%, silt particles average 13%, and clay particles average 8%. The average pH values of the petrogypsic horizon of the soil is about 7.60, which means that the soil can be classified as alkaline. Testing for iron, zinc and organic matter show that the soil has a deficit of these materials, whereas calcium carbonate leverls are very high: about 28%.

The soil water-holding capacity is very low due to the soil texture. Loss of water by deep percolation and soil intake are very high.

2.4.2 Soil Structure and Composition: Saudi Arabia

The soils of Saudi Arabia are heterogeneous but the differences are not great enough to modify the hydrological characteristics. Nevertheless the widespread basalt plateaux are very favourable to filtration and of great importance for the ground water. Plant cover is practically non existent, and therefore does not influence flow. Consequently run-off is very high. The table below shows the relationship between geomorphic zones and the other classifications.

Table 2.1 summarises the soil information available in the area, although this is extremely limited. There is a large variety of soil types. These soils are in a primitive state of development because of the prevailing arid conditions and scarcity of natural vegetation. Out-croppings of partially weathered parent material are also frequent in this area. Accordingly, immature and consolidated accumulations, such as gravelly, rocky or sandy ground in its various forms, is treated here as soil insofar as it supports vegetation without minimising the value of pedogenetical and physico-chemical properties in soil classification.

Alluvial deposits are widespread throughout the area, although they are limited to the valley sides in the mountain range. On the upland plateau of the eastern slopes of the mountain range considerable proportions of alluvial deposits extend into the channels and water courses, and consist of fairly coarse to fine sands, gravels and pebbles. Both fine and loose sands derived from the disintegration of the crystalline rocks on higher foothills through the water courses are deposited extensively in the alluvial plains along the long channels of wadis. Deposits of the quaternary basalts and pyroclastic rock, sometimes with tuffaceous ejecta, occur along the Red Sea coast, from north to south, unconsolidated silt, sand and gravel with coralline detritus occur on the vast plain, and the mechanical composition of the different types of soils kind from pits dug in wadi-Piedmont alluvium and sandy-sabkha soils locations, to illustrate the ratio of coarse deposits to the kinds of the deposits of the sample. The coarse particles in the soil is in the mountain wadis, outwash fans, Piedmont plains and high sand dunes where infiltration is soft.

An attempt is made to identify the locations of the above mentioned topographic, soil and geological classifications in Figure 2.7. A table showing the relationship between the geomorphologic zone and the other classifications is also prepared, and the mechanical composition of a zonal soils through which recharge from rain and flood water is taking place.

Table 2.1:
Relationship between the geomorphic zones and other classifications

Geomorphic classifications	Topographic zones	Soil classifications, type or varieties	Geological origins
Hilly Plateau	around Mountain Range (M.R.)	Hammada (desert soil), Brown, Chestnut and Podosolic soils	Precambrian Hali Schists Older Gneisses and next group
Highly Dissected High Mountains	partly M.R. mostly Upland Plateau (U.P.)	Hammada (Tihama side) and Reg	
Volcano and Lava Flow	ditto		Metamorphosed Breccias
Highly Dissected Plateau and Hills	Upland Plateau and Coastal Plain (C.P.)	Hammada & Reg	Conglomerates, Sandstones, Schists
Terrace	U.P. and C.P.	Loess	Cale-Alkaline Granite
Basin	upstream of wadis in U.P.	Sand and Alluvial soils	'Halaban Andesites
Flood Plain	Coastal Plain	Alluvial Soils	Quaternary Basalts
Coastal Marsh	ditto	Salines	Pyroclastic rock
Sand	U.P. and C.P.	Sand and Saline soils	Tuffaceous eceta

Source: Ministry of Agriculture and Water

The soils are mainly assemblages with considerable amounts of kaolinitic chlorite and some interstratified minerals. These minerals could be considered of detrital origin. On the other hand, the soils on sandstone are kaolinitic with minor amounts of illite. The reddish sandstone is mostly of a well-crystalline type (Al-Sharif, 1977).

The results of the soil surveys indicate that the soils are derived from the limestone and marl formations; eolian desert sand of tidal sediments of the Arabian Gulf; and desert sand. There is a hard pan at a depth of 50-70 cm. The texture of the soil has been classified as sandy with gypsum and loamy sand with gypsum, coarse textured loamy sand and medium textured coarse sand. There are considerable amounts of soluble salts in the soil consisting of gypsum and calcium carbonate.

The extreme of soil formation is the development of laterite, a soil in which the upper portion is strongly depleted of all but clay minerals, iron oxides, and perhaps quartz and the lower zones are enriched in downward transported iron and aluminium oxides and hydroxides (Knapp, 1983). Soil formed of aggregates that disintegrate when wetted have little advantage over pulverised soils. They vary greatly in their sub-soil and often appear as extensive, undulating gravelly plains intersected by hills, gulleys or runnels. Most of the hammada and reg areas are very sparsely vegetated. There is a diversity of sandy soil in the form of dunes, sandy hammada and sand flats, depending on altitudes, physical properties, mobility and lithological origin. The soil materials are originally transported by wind and water from adjacent higher sites. These material often cover extensive plains and wadis, at times interrupted by hills and remnants of former plateaus that have disappeared through weathering and erosion. Other types are relatively extensive on the steppes in the area. They often sustain a rich herbaceous vegetation, and have mostly been put to grazing long ago. The occurrence of a number of different plant communities in the area stems largely from the diversity of prevailing edaphic conditions (Knapp, 1983). A number of reconnaissance soil surveys have been made in different areas of Saudi Arabia under hydro-agricultural surveys since 1966. Some detailed soil surveys and land classification for many of these areas are presently in progress. A general soil map for Saudi Arabia was also drawn, prepared with the aid of satellite and other remotely sensed data and ground studies. Soils consist of a sequence of layers or horizons. There are many different kinds of horizons. Some of the more common and distinctive horizons have been defined and selected as diagnostic horizons in the classification system. In the higher categories of taxonomy, definitions of classes are based in large part on the presence or absence of the horizons.

Saudi Arabia has three main soil regions, namely the Coastal plains, the Arabian Shield, and the Sedimentary Basin. With the exception of numerous wadis and oases in those regions, the soils are generally coarse textured and shallow overlying lithic or paralithic. Gypsic or calcic horizons are often present in the subsoil. The common soils in these zones are members of the great soil groups, Torripsamnents, Calciorthids and Gypsiorthids, while the Psamnents consist of sand dunes and cover 40% of Saudi Arabia mainly the great three deserts, the Great Nafud, Rub-al-Khali and the Dahna Deserts. The aridity of the climate combined with the physiographic features of the country has resulted in the mostly saline and alkaline desert soils that cover a large part of the country. Salt affected soils occur in the coastal zones in closed basins (sabkhas) and in irrigated areas where drainage is inadequate. Land suitable for irrigated agriculture is limited to wadis and oases scattered throughout the country. These lands are composed of recent alluvial soil generally deep and finer in texture. The common soils are members of the great soil groups: Torriorthents and Torrifluvants.

Areas with irrigable soils are found throughout Saudi Arabia. Major tracts of these areas are found near Qasim, Hail, Kharj, Wadi Dawasir, Sulayyil and the Rub-al-Khali. Other areas having extensive irrigable tracts are Tabuk, Jauf, Tayma, Zulfi, Hufuf, Shaqra, Layla and the Tihama (Al-Sharif, 1977). The dominant soils of the above identified areas are primarily Calciorthids, Torripsamments and Gypsiorthids, Torrifluvants, and Salorthids are also present.

2.4.3 Landform and Soil Genesis in Tihama Asir

The land surface of Tihama Asirhas an overall east to west slope down towards the Red Sea of under 0.5%. Locally, the land surface is frequently dominated by the microtopography which is largely induced by erosion caused by poorly controlled flood water. The aquifer field bounds, which may be up to 3 m tall, are featured throughout the surveyed area. The soils are all alluvial, colluvial or aeolian in origin and show little sign of pedogenetic development. Man's influence in controlling and distributing the floods, and hence the flood sediment, has had a profound effect on the build up of the finer textured alluvial soils of the region.

The wadis' soils were essentially differentiated on the basis of their overall textured profile and on the presence or absence of older, redder and more compact sediments in the top 75cm of the soil. The additional symbols are as follows:

a. low to medium dykes enclosing medium to large fields;

b. medium and high dykes enclosing small and medium fields;

c. slight differences in field levels;

d. major differences in field levels.

There are limits to the work area, because of the constraints imposed by both soil type and water availability. Only 10,000 ha were scheduled for soil investigation. The limits were not precisely fixed before the commencement of the work. It was felt that this decision could best be made in the field, where the relevant information about land, soil and water rights would be more readily available.

The areas subject to water rights were not materially at variance with areas selected on soils and land form criteria. Land with water rights had over the years usually become the better soils of the wadi by virtue of the accumulation of silty sediment deposited by the floods.

2.4.4 Soils structure and composition in Tihama Asir

In the absence of any marked pedogenetic development the soils are dominated by the characteristics invented from the dispositional sediments, in particular by texture and stratification. The natural structural lamination of the sediment is largely destroyed by the immediate post flood cultivation techniques, which break the successive new surface horizon into a structureless or weakly sub angular influenced by the texture, is fairly uniform through the wadis.

The soils of relevance to agriculture are found mainly in the wadis and plains associated with the schist bedrock of the Tihama Asir range. The humus content of the soil is generally low due to rapid decomposition of organic matter and they are also poor in potassium and phosphorous. Figure 2.7a-b show crudely shaped patterns in wadi soils in Tihama Asir. Winter rain readily infiltrates the deep regolith and pervious bedrock of limestone. The dry soil supports only low shrubs. Detailed studies of the soils and land distribution show them to be quaternary sediments, mainly alluvial, ranging from sands to clay loams. Soil texture ranges from course, silty clay loams to light loams in the upper wadis. In areas of north and south Tihama Asir soils become loams and sandy loams. Further, beyond the preceding villages, substantial areas of fine, and medium, texture soil continue. Soil colours vary from dark brown to dark yellow-brown, and in some cases red is observable. With respect to soil structure, the most distinct depositional features are the platy structures of medium and fine textured flood sediments (Mohammad, 1985)

The content of exchangeable bases is adequate but the levels of nitrogen and phosphorous are frequently low, although no specific nutrient deficiency symptoms of these minerals have been observed under the existing crop pattern. From the present study it seems clear that some nutrient replenishment does occur from fresh flood sediment, although not to the degree that had previously been supposed.

The soils of Tihama Asir are classified as follows:

Calciorthids are the most widely spread group, and associated with the uplands plains, the narrow plains of the highlands and sand plains. They are deep, medium to coarse textured calcareous soils, having a horizon of calcium carbonate accumulated within 100 cm of soil surface.

Figure 2.7a: Soil overlying gravel and weathered rock in Tihama Asir (slightly hard when dry, friable when moist)

Figure 2.7b: Sandy and fine sediments composed of silt loam and fine sandy loam

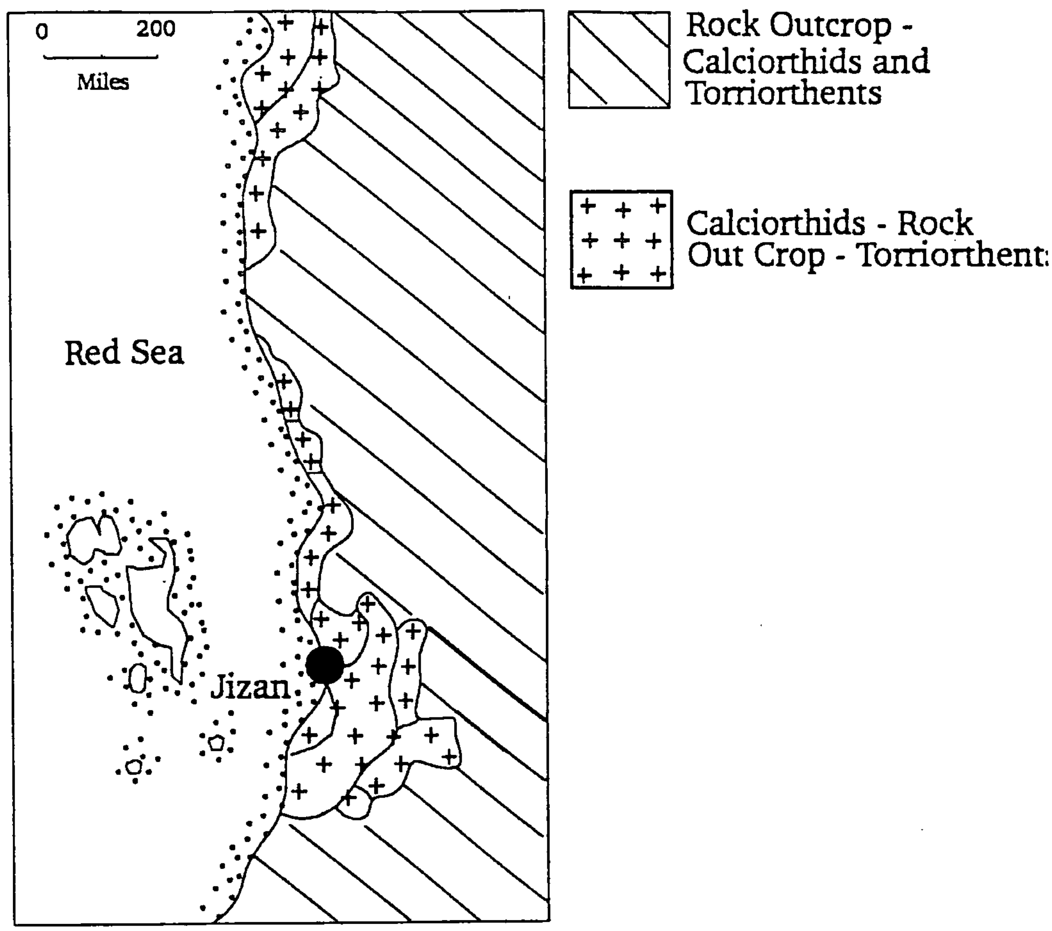
Torripsamnents are the second most extensive and more common in the upland plains, dissected high land and alluvial-colluvial fans. These soils are shallow and coarse textured, having more than 35% gravel within 100 cm of the soil surface.

Torrifluvants are limited in extent but are the most important soils in the study area for agricultural development. These are confined to wadi alluvium and are deep medium to fine textured calcareous soils, with no impervious layers within the 100 cm depth (Al-Sharif, 1977).

The soils of Saudi Arabia belong either to the Aridsols or the Entisols. The dominant sub-order of the Aridisol is the orthids, whilst the dominant sub-orders of the Entisols are the Psamnents, the Fluvants and the Orthants. Calciorthids are the most wide-spread great soils of the Orthids. The Fluvants are almost exclusively confined to wadi areas, that is, wadi bottoms, wadi flood plains, terraces and adjacent plains extending as far as 5 km on both sides of the wadis. The Psamnents extend across different physiographic units, being spread throughout the area except in the highlands where little or no Psamnents have been found.

Figure 2.8 summarises information about soils in Tihama Asir. The four soil types are calciorthids: rock outcrops; torriorthents: deep, loamy, arable soils and rock outcrop; and rock outcrop calciorthids and torriorthents. Rock outcrop and loamy, non-arable soils are found distributed throughout the area in the wadis, in the foot hills and in the coastal plain near Jizan City. That is, since the classification of the soils of the area was based on the nature of the texture profile, as well as overall moisture capacity and suitability for irrigation agriculture, the land classification frequently followed those of the depositional soil series as in the Figure 2.7a-b. The factors influencing land capability, such as soil texture, nutrient status, drainage, and land form were taken into consideration. The classification is based on the flow and origin of soil

Figure 2.8: Soil association map of Tihama Asir



material, developments and texture. Soil texture ranges from coarser, silty clay loams to light loams near the foothills, and soils become loams and sandy loams near the coast. With respect to soil structure, the most distinct depositional features are the platy structures of medium and fine textured flood sediments.

The local topography and soil types are intimately bound up. This is illustrated by the following. During one of the periods of the Pleistocene, the wadi systems carried rushing floods loaded with rock debris, eroded from the crystalline and sedimentary upland of the Asir mountains. The floods cut narrow, steep-sided canyons through upland and then, as the flood spread out onto the low-lying plains, they dropped their load in a delta-shaped area. The surface of the area is now a gentle sloping gravel plain, covered with gravel terrain in many places. Other gravel beds have been observed in the wadi walls of Wadi Hali and elsewhere. Cobbles and pebbles show a gradual decrease in size towards the outer edges. They are composed of quartz, igneous rocks, metamorphic rock and sometimes limestone, with finer sediments interspersed. Deflation by wind has smoothed the plain into a very flat, gentle undulating surface, veneered with gravel. When dry, it is traversable by vehicles in any direction (Mohammad, 1985).

The soils of the wadis are mainly sand to sandy loam, mostly loose to very loose, especially in the middle parts and lower parts of the wadi courses. The soil types are scattered widely due to their geological origin, as random fluviatic and aeolian sediments. All soils are low in organic matter. At deeper layers the soils are sometimes slightly hard when dry, but friable when moist.

Located on the stream terrace positions, there are deep well-drained loamy soils found on the alluvial plains which are dissected by small shallow wadis. The surface of most is covered by a thin layer of gravel. Much of this area is currently being used for rangeland. In some areas where water is available they are used for irrigated crops. This soil is suited to large scale irrigation. Many individual soil areas are extensive and rectangular shaped.

2.5 Climate in Saudi Arabia

Climate is concerned with features of global and local air masses. These features include air temperature, wind speed, humidity and precipitation. Also included are solar and ground radiation, and the interaction between the air masses and local topography. Proximity, or otherwise, to significant bodies of water often has a major effect on local or regional climates. Climate around the world tends to be classified in terms of annual and seasonal rainfall, and average and range of temperatures.

Climate in general is the dominant physical factor affecting water resources. An understanding of their characteristics and spatial variation is essential for evaluating, planning and managing conventional water resources.

Saudi Arabia is mainly an arid country, though it is affected in the south by the south west monsoon during the period June to August, and by the Mediterranean depressions from the north during the period October to May which bring some rain. While there are areas which experience rainfall each year, there are many areas which do not record rainfall for several consecutive years. Climatic stations in the north of the country generally do not experience rainfall during the period June to September, while others in the south west have the main rainy season during the period April to August (Lockwood, 1985).

Though the country can be taken generally as an arid zone, there are high mountains in Asir which exhibit a range of climatic types; the mountainous climate on the high peaks, the interior regions, and the coastal areas. However, the arid climate which composes the major part of the country can be classified as a hot desert type.

Saudi Arabia in general can be described as a tropical and sub tropical desert linked climatically to the eastern Mediterranean and adjacent lands. Air masses that influence its climate move into the country mainly from the north and west. Climatic influences from tropical zones to the south tend to be blocked by the mountains that run from Oman through the Yemen.

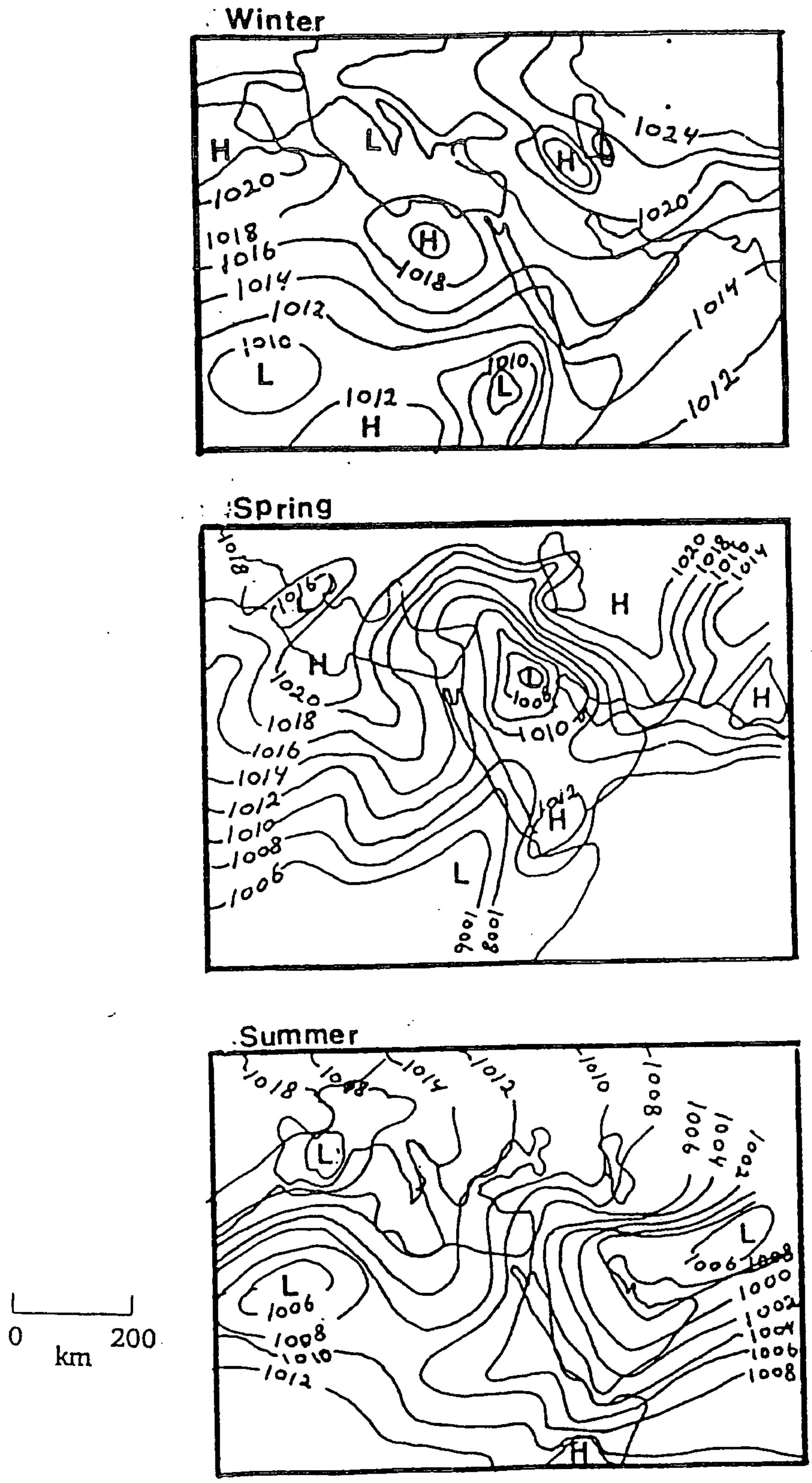
Given that Saudi Arabia is overall arid, moisture properties and the national utilisation of water are of critical interest for national development. This is especially true for the agricultural sector. Saudi Arabia, with only a few exceptions, is a hot, dry desert. There are three sub-climatic regions that may be distinguished within the country, according to Köppen-Geiger climatic classification (1953). These are the coastal, the interior, and the highland regions. In this study, the general climatic aspects of Saudi Arabia are described. Saudi Arabia has extreme temperatures and dry climate due to its latitudinal location and its overall continental position in spite of being a peninsula (Al-Sharif, 1977; Noury, 1983).

Saudi Arabia is bounded by water on two sides, yet aridity is its dominant climatic feature. The high temperature and the dryness of the air results from climatic and physical influences including general air circulation, location of moisture sources, and especially the mountainous barriers in the west. The sole exception to the otherwise universal aridity of Saudi Arabia is in the Asir region which receives abundant monsoon rainfall during the summer, because of its unique geographic and topographic features. The Mediterranean depressions from the north during other seasons bring some rain to Saudi Arabia. Whilst there are areas which experience some rainfall each year, there are many areas which record no rainfall for several consecutive years.

Though Saudi Arabia can be generally considered an arid area, and classified as a hot desert climate, the high mountains of Asir exhibit a range of climatic types: mountain climate on the high peaks, steppe regions on the lower peaks of the escarpment, and arid conditions which prevail on the lower slopes.

Not surprisingly, the climate of Saudi Arabia is somewhat more complex than the above simplification would suggest. Part or all of the country can be affected by polar air masses which may be dry or humid, while other parts are affected by dry or humid tropical air masses. These air masses are supreme over either the country or over the surrounding regions, and thus give very variable weather conditions from year to year. During the period October to May, the prevalent air masses are the Continental polar air mass which develops over Central Asia and the Iranian-Baluchistan plateau; the Maritime polar air mass which develops over the Atlantic Ocean and extends eastwards over Europe and south eastwards where it becomes modified during its passage across the Mediterranean Basin; and the Continental tropical air mass which builds up over the Sahara. During the period June to September, the prevalent air masses are the tropical air masses of thermal low-pressure which cover an area extending from northwest India to North Africa through Arabia, and the Maritime tropical air mass which originally develops over the Indian Ocean and the Arabian Sea. Because of this complexity and also the lack of long term climatic records one cannot at present study the climate of this country without encountering some difficulties. (Figure 2.9)

Figure 2.9: Air mass in Saudi Arabia



The climate of the Arabian Peninsula falls within C.W. Thornthwaite's (1931) 'arid province' and within W. Köppens (1900) 'dry climate', except for parts of north and south Yemen, the Asir Province of Saudi Arabia and northeastern Oman, where the temperatures are lower, the rainfall is greater than in the remaining part of the peninsula, and where vegetation consists of mountain forest and woodland.

Saudi Arabia tends to derive its weather from the north and west. Climatically it is linked to the eastern Mediterranean and adjacent lands, in that it has a long, hot and almost totally dry summer, with a short cool winter season during which a little rain occurs. This is because air masses reaching Arabia have been largely exhausted of their moisture. Although Arabia is surrounded from three sides by sea, aridity is the dominant feature. With the sole exception of Asir in the south west, any influences from the southern tropical zones are excluded by the highland rain that runs from Oman through Southern Yemen to Northern Yemen (Rajab, 1978). Because of the dryness of the air reaching Saudi Arabia, and the consequent lack of clouds, isolation is considerable, producing very high summer temperatures up to 50°C, and sometimes higher in the southern deserts. The absence of clouds allows heat to escape from the surface at night, so temperatures drop quite markedly from day to night, and also from summer to winter. The night coolness, with a 10°C to 22°C drop during both seasons, is a boon in summer but leads to the sporadic appearance of frost in the central and northern regions during winter. Temperatures as low as 7°C have been recorded in Riyadh.

The climate of Tihama (see Section 2.5) can be divided into two areas: the coastal region and the mountains. To the south of Jeddah, the climate is tropical to sub-tropical, dry rather than wet, and much influenced by the effect of high mountains. There are two main seasons: monsoon rains with a sharp but highly variable peak in

July-August; and winter rains with a much smaller but more regular peak in January, although rains can in fact occur in almost any month of the year. The average annual rainfall diminishes noticeably in any direction away from the region. In the mountainous region there rainfall ranges between 250 mm and 600 mm, and on the coast between 50 mm and 250 mm. Temperatures are as a rule very high, with peaks of about 48°C and minimum levels of some 15°C. Relative humidity is always very high.

When air temperature is warmer than ground temperature, the air loses heat both to the atmosphere by convection, and to the ground by conduction. When air temperature is cooler than ground temperature, the air gains heat from the ground by conduction, but loses it to the atmosphere by convection. Evaporation is enhanced by high temperatures, low humidity and advective winds. These factors are described in the following subsections.

Metabolic processes may release heat or may consume energy. Satisfying and balancing the energy requirement largely depends on climatic conditions in Saudi Arabia (Craig *et al*, 1963).

2.5.1 Radiation and temperature in Saudi Arabia

The earth and its atmosphere receive heat energy from the sun: solar insolation. At the top of the atmosphere the flux density of solar radiation is estimated to be 2.0 langleys/minute. Some of this energy is absorbed by the earth and its atmosphere, and some is returned to outer space, partly as a result of scattering and reflection by clouds and other atmospheric constituents, but much of it due to heat radiation from the earth. An energy balance is maintained whereby the earth and atmosphere as a whole are becoming neither hotter nor colder. Accordingly, present climatic conditions remain stable.

As the earth's surface absorbs shorter wavelength solar energy, its temperature rises. All bodies naturally radiate long wavelength energy (infra-red radiation), and the hotter they become, the more intense the energy radiated. As the earth's surface increases in temperature, the intensity of the infra-red radiation increases. The atmosphere, unable to absorb the shorter wavelength radiation, is able to absorb infra-red radiation, and as a consequence heats up as the ground temperature rises. In summary: although the atmosphere absorbs little enery directly from incoming radiation, it absorbs much radiation from the earth, and is thus heated from below. Much of this atmospheric heat is stored in clouds and water vapour. The total number of hours of sunshine during the day is primarily a function of latitude and season. Saudi Arabia lies in the tropical and sub-tropical zone, which determines the number of daylight hours during the summer. On 21 June each year, daylight lasts between 13 and 14 hours. During winter, however, the length of the day is considerably shorter. The average number of hours of sunshine recorded in any particular month tends to be consistently smaller than the maximum possible because of cloud cover resulting from seasonal weather systems moving across the country (Al-Sharif, 1977).

The interior parts of Saudi Arabia are mostly under cloudless conditions compared to the south western and northern regions. However, dusty conditions during certain times of the year have a significant effect on the intensity of solar radiation reaching the eastern, central and north-central regions of Saudi Arabia. The country's mean maximum solar radiation is about 600 langleys/day between June and July (Noury, 1983). Since air and water temperature are largely dependent upon energy derived from solar radiation, it is to be expected that there will be a fairly close correlation between air and water temperature and the rate of evaporation. The temperature of the water surface, be it open water or moist soil is important in that it affects the rate of evaporation. Plants, on the other hand transpire at a rate which, less dependent on the temperature of their leaf surfaces, depends on rate of plant growth.

During the summer the area comes under the influence of hot, dry air. Partially clear conditions at altitude do little to lower the temperature, and clouds drift towards the Asir Mountains due to the prevailing westerly winds aloft during October to May and thus produce rain over the area. Radiation flux density declines as the angle of impact of the rays moves away from the perpendicular. The sun's rays have a reduced heating effect on sloping ground. Sunlit and shaded slopes in close proximity can show striking differences in surface temperature. The surface of a flat, enclosed or concave wadi in the low latitudes can become very hot, and transfer its heat to the air above.

Air temperature in Saudi Arabia varies between seasons and between regions, and is controlled by three main factors: elevation, radiation and water body movements.

(1) As elevation increases, temperature decreases.

(2) Solar radiation is intense most of the year, as described above.

(3) Air masses moving in from the Mediterranean tend to be cooler than those moving in from the Indian Ocean.

Saudi Arabia is mainly a plateau of modest elevation. Most of the country is below 800m, and only about 3% of the land area is above 2,000m. Therefore temperature decrease due to altitude plays a relatively minor role in the climate of Saudi Arabia.

Because of the narrowness of the immediately surrounding water bodies, the direction of the prevailing winds and the peculiar layout of the highlands which extend along the Red Sea Coastal Plain as a barrier, the influence of these water bodies is limited to land in their immediate vicinity. It is seldom that they play an important part in the control of temperature of the areas beyond the narrow coastal strips (MAW).

The Saudi climate consists of a dry, hot summer, especially in the northern and central areas. In the southwest, where Sarawat Mountain rises to 2,750 m, summer temperature usually drop as low as 10°C. Winter temperature are generally fair to cold at night, sometimes falling to freezing point, especially in Al-Hijaz and Asir Mountains in the northern part of Saudi Arabia. In coastal areas, particularly on the Red Sea coast, temperatures remain warm to fair all winter. The temperature range is wide, especially between day and night, and there are great precipitation and temperature differences between one region and another (MAW). The mean annual temperature is of little significance and may be misleading in a study of temperature in an arid area like Saudi Arabia, because it conceals the maximum and minimum temperature conditions, which are substantially different between summer and winter.

One climatic feature of the area is the cool winters, which are associated with domination of high pressure weather systems over the country and lower solar insolation during the winter months. The average mean temperature (Table 2.2), for the coldest months (December to February) in Riyadh is 19.7°C. Dhahran, on the east coast, has a temperature of around 19.8°C. Taif, on the highland, has a range around 17.0°C. Ha'il, in the north desert, has a mean of 14.1°C. Najran, in the south desert, has a mean of 16.7°C. That the climate tends to be dominated

Table 2.2

MINIMUM TEMPERATURE (°C) ACCORDING TO METEOROLOGICAL STATIONS , 1990.

City Month	Najran	Jouf	Jizan	Qaseem	Ha'il	Tabouk	Ta'if	Medina	Dhahran	Jeddah	Riyadh
January	10.5	1.4	24.0	6.1	2.6	2.7	9.4	11.4	9.8	18.9	9.0
February	12.2	4.5	24.1	8.8	4.5	5.3	10.9	13.0	12.7	19.6	11.7
March	14.2	9.3	25.7	13.7	9.6	9.8	13.4	17.4	16.2	21.4	16.6
April	17.5	14.0	26.0	18.7	15.2	14.1	17.1	22.3	20.1	23.2	21.5
May	21.0	18.0	27.7	22.7	20.3	18.1	19.3	25.1	23.5	25.4	24.9
June	21.5	22.2	29.3	23.8	21.7	21.5	22.4	27.7	26.6	26.3	26.4
July	24.8	23.2	30.2	26.1	25.1	22.7	26.2	27.9	28.4	28.2	29.0
August	24.0	22.9	28.7	24.2	21.2	22.4	23.9	27.7	26.9	27.9	27.1
September	20.2	20.0	27.1	21.5	18.6	19.9	21.8	26.7	24.2	26.7	24.8
October	15.4	15.8	25.8	17.8	14.0	15.9	17.0	22.8	20.8	24.7	20.1
November	11.7	11.2	23.9	15.9	11.0	12.1	13.3	18.1	17.7	23.5	16.7
December	7.4	7.5	21.3	7.7	4.9	6.4	9.1	11.7	10.4	20.1	19.1
Average	16.7	14.2	26.2	17.3	14.1	14.2	17.0	2.0	19.8	23.8	19.7

Source: General Meteorological Department.

Table 2.3

MAXIMUM TEMPERATURE (°C) ACCORDING TO METEOROLOGICAL STATIONS , 1990.

City Month	Najran	Jouf	Jizan	Qaseem	Ha'il	Tabouk	Ta'if	Medina	Dhahran	Jeddah	Riyadh
January	25.2	15.4	30.9	19.5	17.5	18.2	21.8	24.8	20.0	28.9	20.2
February	28.3	16.6	31.1	20.7	18.6	18.9	24.1	26.0	21.6	28.4	22.6
March	29.5	23.4	32.8	32.5	24.9	25.7	26.8	31.5	27.6	32.0	30.0
April	34.9	28.5	34.8	37.6	29.3	30.4	31.0	36.3	33.7	33.5	34.8
May	37.3	34.2	37.4	40.8	34.4	35.7	33.3	40.1	38.3	36.7	38.9
June	39.1	38.6	37.8	42.1	38.4	38.7	35.1	42.3	42.8	36.2	42.1
July	40.3	39.8	37.2	41.1	39.4	39.1	34.5	42.2	44.0	38.3	43.7
August	39.2	38.5	37.4	38.9	38.6	38.6	35.2	41.4	42.6	37.5	42.3
September	35.2	36.0	37.1	34.8	35.2	36.9	34.3	41.4	39.8	35.6	39.9
October	32.5	30.9	35.9	25.1	31.5	32.4	31.5	37.6	35.6	35.1	35.3
November	28.1	22.9	33.4	19.5	24.2	26.4	26.8	30.6	29.2	33.0	28.8
December	25.5	18.3	30.6		19.1	21.0	23.9	25.5	23.0	29.6	22.2
Average	32.9	28.6	34.7	31.7	29.3	30.2	29.9	35.0	33.2	33.7	33.4

Source: General Meteorological Department.

by a cold, dry, continental, high atmospheric pressure air mass extending from Siberia and Central Asia southwards. This has the effect of decreasing the temperature and producing clear, dry weather. When the influence of the air mass diminishes, another air mass from Atlantic and European sources moves towards Saudi Arabia across the Mediterranean. This air mass is characteristically warmer and moister than the Asian air mass, and brings rainfall to the northern and western regions of Saudi Arabia.

The mean monthly air temperature during the winter is between 14°C and 26°C over much of Saudi Arabia. The mean temperature may drop below this in the northernmost areas and in the highland. The maritime influences of the Red Sea and Arabian Gulf do not appear to penetrate far inland since the wind direction in winter is predominantly the persistent north-west wind which blows off the land, and the western highland prevent modification, limiting maritime effects to the coastal strips.

The summer is the longest season, lasting from May to September. During this period, most of Saudi Arabia is predominantly influenced by a hot, dry continental tropical air mass which produces stable meteorological conditions. The sun is at its northernmost reach, causing intense solar radiation. The weather throughout most of the country is clear, very hot and dry. The only area which does not normally experience this situation is Asir and southern Hijaz highlands, where the moist and tropical air mass is accompanied by rainy tropical depressions and cyclones which bring summer rainfall. The average maximum temperature (Table 2.3), for the hot months are as follows: In Riyadh it is 33.4°C; Jeddah, on the west coast, has a mean of 33.7°C; Dhahran, on the east coast, has 33.2°C; Taif, on the highland, has a mean of 29.9°C. Hail, in the north desert, has 29.3°C; Najran, in the south desert, has 39.9°C. Actual temperatures are usually higher as little shade exists, as is required for official temperature readings.

Figure 2.10 gives air temperature in Saudi Arabia and shows that the monthly mean is very high. Mean temperatures are normally over 30°C, and the absolute maximum inland may exceed 50°C. Thus, it is expected that diurnal and annual ranges are wide, though in coastal areas both diurnal and annual ranges are smaller. There are great precipitation and temperature differences between regions. For instance, the Rub al Khali can reach temperatures over 50°C, central Saudi Arabia normally experiences temperatures of between 18°C and 30°C, whereas over the highlands the temperature can be lower than 18°C.

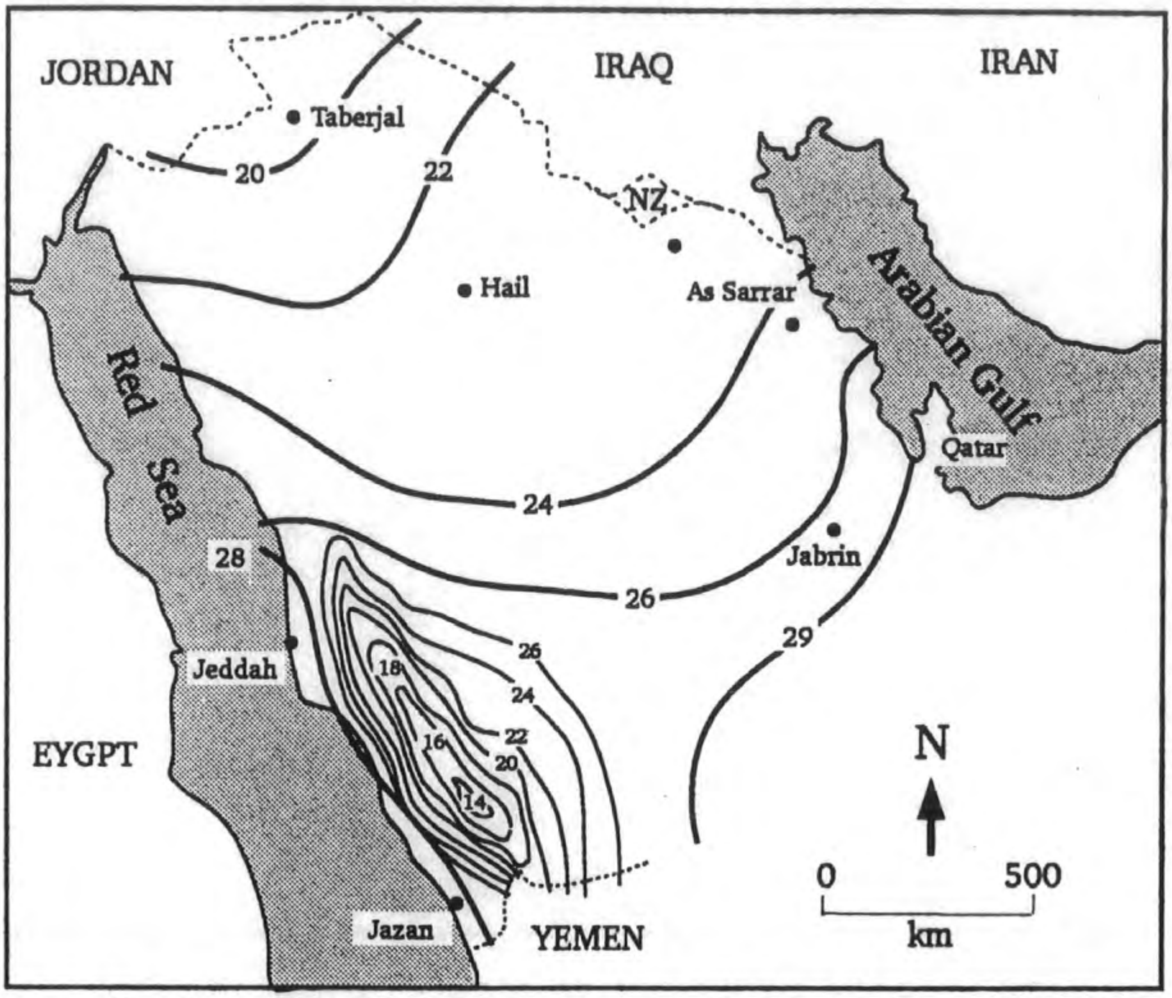
Figure 2.10 shows the distribution of the mean annual temperature. It is easy to recognise the temperature distribution and the north-south gradient, as well as the east-west temperature gradients toward the western highlands. It is also easy to notice the warmest and coldest areas in Saudi Arabia during the year. Temperate conditions dominate the country when the air temperature seasonal range is between 14 and 26°C over the major part of Saudi Arabia.

(1) Summer

Summer is the longest season, lasting from late May to September. During this period, most of Saudi Arabia is predominantly influenced by a hot, dry continental tropical air-mass which produces stable meteorological conditions. The sun is at its northernmost reach, causing intense solar radiation. The weather throughout most of the country is clear, very hot and dry. Change does not occur until September.

The cloudless skies over most of Saudi Arabia, coupled with the dry air, the predominance of the continentality, and the high solar insolation, cause air temperature to be very high during the afternoon where the absolute maximum temperatures may exceed 50°C. Since the country is a vast land mass, and the maritime influences are limited to minor areas, the air temperature during the night may drop below 30°C.

Figure 2.10: *Mean annual temperature °C*



Source: - Kingdom of Saudi Arabia Ministry of Agriculture (With Some Modifications)

July is the hottest month over most of the country, though the highest absolute maximum may be recorded in June or August, in this season the differences in temperature between one area to another are smaller than those found during the cool season. In the littoral areas the weather is oppressive, due to high humidities, while only a short distance from these littoral areas the heat is intense during the day and air temperature is high at night.

The only area which does not normally experience this situation is Asir and southern Hijaz highlands, where the moist and tropical air-mass is accompanied by rainy tropical depressions and cyclones which bring summer rainfall (MAW).

(2) Winter

Winter lasts from early December to February. The climate tends to be dominated by a cold, dry, continental, high atmospheric pressure air mass extending from Siberia and Central Asia southwards. This has the effect of decreasing the temperature and producing clear, dry weather. When the influence of this air-mass diminishes, another air-mass from the Atlantic and European sources moves towards Saudi Arabia across the Mediterranean. This air-mass is characteristically warmer and moister than the Asian air-mass, and brings rainfall to the northern and western regions of Saudi Arabia.

The mean monthly air temperature during winter is between 14°C and 20°C over much of Saudi Arabia. The mean temperature may drop below this in the northernmost areas and in the Asir Mountains. Frost over most central areas in not impossible. Snow has been reported in the high western mountains. The maritime influences of the Red Sea and Arabian Gulf do not appear to penetrate far inland since the wind direction in winter is predominantly the persistent north-west wind which blows off the land, and the western highlands prevent modification, limiting maritime effects to the coastal strips (MAW).

The warmest areas in Saudi Arabia during the winter are the littoral regions along the Red Sea in the west and the Arabian Gulf in the east. Since the littoral areas extend from the south east towards the north west, air temperatures decrease in this direction. The mean temperature of the winter months is constantly over 15°C at all the climatic stations located in the coastal plains.

In the coastal plan of the Arabian Gulf there are eight stations recording air temperature. Three of them are located close to each other on the coastal plain and two other stations are located in the hinterland and seem to be affected by the continental conditions that dominate the inland, rather than being influenced by the maritime effects of the Arabian Gulf. However, as the coastal plain of the area extends from the south east toward the north west, there is a temperature gradient in this direction.

The mean monthly temperature in winter over the Arabian Gulf coastal plain is normally over 15°C, though it may drop to less than this value in the northern part of the area.

The coldest areas all over the country during the winter months are the Asir highlands and the northern province. The means monthly temperature of the winter months in these two cold areas normally ranges between 4 and 12°C in Asir, and between 6 and 11°C in the northern province. In both areas the minimum temperature is normally recorded in January. Away from these two regions the prevailing conditions are more temperate, though a low temperature at 0°C or -2°C may be recorded in the interior of the country for three to five days during January or February.

Therefore, to the difference in the values of air temperature between the cool season and the hot season, there is a difference in the regime of temperature between the two seasons. During the cool season there are remarkable fluctuations of temperature. These considerable increases and decreases of temperature in the cool season are mainly caused by the sudden incursion of either cold polar air, or hot, dry air; during the hot season, air temperatures all over Saudi Arabia are persistently high, with maximum during the day and minimum at night. However, all over the entire country there is a significant temperature gradient from the south toward the north where air temperature again is lowest. Moreover, there is an east-west temperature gradient from Najd sedimentary plain toward the Asir and southern Hijaz mountains, a west-east temperature gradient is found to occur from the coastal plain of the Red Sea towards the escarpment of Asir and Hijaz. The only air temperature gradient that can be studied in detail is the south-north temperature gradient, although some indications about the east-west and west-east temperature gradients can be made.

2.5.2 Relative humidity in Saudi Arabia

Water evaporates from exposed water surfaces and from moist ground. Plants transpire. These processes transfer water molecules, in the form of water vapour, into the atmosphere. Absolute humidity is the actual amount of water vapour present in a unit volume of air, and is expressed in g/m^3. Relative humidity is a measure of the proportion, expressed as a percentage, of water vapour in the air relative to the maximum load of water vapour the air (at any given temperature and pressure) can carry. When the air is saturated with water vapour, its saturation vapour pressure has been reached. The amount of water vapour the air is able to carry before becoming saturated depends on air temperature and atmospheric pressure, and therefore also altitude. The mean vapour content of air at 1200m may be only about a tenth of air at sea level. At sea level, air tends to be by volume about 2% water vapour, although this figure can vary from 0% to 5%. However, relative humidity can vary from 0% to 100% at either altitude (MAW).

Relative humidity is closely related to temperature. With constant air moisture, relative humidity increases as the temperature decreases and vice versa. Relative humidity, as a result, is likely to be at its maximum level when temperature is at its lowest point. For this reason, winter always has the highest relative humidity. The direct relationship between the actual humidity of the air and the rate of evaporation is discussed below. However, there is considerable variation in relative humidity during the year. For example, the range in values between the highest value (January) and lowest value (June) is 33.40%. During the winter, it is very high due to the rainfall, reduced evaporation and low temperature (MAW). Since relative humidity increases as the air temperature falls, even though the water vapour content of the air remains constant, if other conditions remain constant, a decrease in temperature will cause a decrease in the rate of evaporation. Thus, in cold weather evaporation is lower than in hot weather simply because the overlying air is able to hold less water vapour before reaching saturation level.

There is a close relationship between relative humidity and evaporation rate. The mean annual cloud cover in Saudi Arabia is less than 20% except for the coastal areas, where the annual cloud cover averages are between 20% and 40%. It is, therefore, understandable that potential evaporation is far in excess of precipitation (MAW). Although Saudi Arabia is bordered by water on two sides, the relative humidity is low throughout the interior. In general, the relative humidity is at its minimum during the summer months and maximum in the winter. As one moves from coastal areas to the interior, the relative humidity drops. The relative humidity has minimum seasonal variation inland; whereas in coastal areas, it is high all year round, due to the high evaporation during summer and cooler temperatures during winter. This is seen in Table 2.4 which gives the mean monthly minimum, and annual relative humidity is generally lowest during the summer months (June-August), with a monthly average of 6%; the minimum weekly average of 2% occurring during the period 30 June to 6 July. The winter months (December-February) have the highest relative humidity, with a minimum of 27%. In 1986, the mean annual humidity was 13% in Medina and 38% in Jeddah. This difference is largely attributable to rainfall distribution. The highest monthly relative humidity occurs during the rainy season (November to March), characterised by clouds and prevailing northerly winds. Mean monthly and annual relative humidities vary from place to place, and change from year to year. However, the variation is much smaller than for precipitation values. The monthly mean covers the whole country. The highest mean relative humidity is in the east and west coasts, and lowest in the mountain and the desert foreland. As stated above, inland areas of Saudi Arabia experience their highest relative humidities during the winter months, ranging from 22% to 53%, and their lowest during the summer months, ranging from 5% to 20%. A similar situation of high relative humidity, but with less pronounced fluctuations, is found during the winter along the Arabian Gulf, ranging from 37% to 54%, and low relative humidities for the summer months ranging from 10% to 17%. The Red Sea area shows a completely different picture. Jeddah and Jizan show a more or less even relative humidity throughout the year, ranging from 35% to 63% (MAW).

In the case of Jizan, the high relative humidity but low rainfall is due to the proximity of the Red Sea but absence of topographic features capable of pushing the humid air to higher, and therefore cooler, altitudes. Evaporation from the Red Sea and the Arabian Gulf causes high humidity in the coastal areas in the summer. The coastal

Table 2.4: Minimum relative humidity according to meteorological stations, 1986 A.D.

City / Month	Najran	Jouf	Jizan	Qaseem	Ha'il	Tabouk	Ta'if	Medina	Dhahran	Jeddah	Riyadh
January	24	31	63	27	42	23	43	20	50	38	30
February	23	31	61	28	45	26	39	19	54	39	28
March	23	20	58	17	44	16	35	14	44	39	16
April	12	10	53	16	33	9	28	11	27	38	13
May	10	8	48	16	21	6	22	8	21	35	9
June	6	7	49	9	20	6	13	5	10	34	5
July	7	6	48	7	19	7	10	6	15	29	7
August	12	9	49	8	16	10	12	7	17	36	7
September	12	10	50	10	18	9	15	7	21	46	7
October	18	14	51	17	20	14	20	11	23	43	10
November	27	36	56	41	41	25	47	21	43	39	21
December	27	39	57	53	48	28	32	21	37	42	22
Average	17	18	54	21	31	15	26	13	30	38	15

Source : General Meteorological Department plains of Tihama and Jeddah in the west, around Dhahran in the east and Jizan in the south west, experience higher humidities than other localities, and relative humidity is reported to reach over 90%. For example, Jeddah experiences a relative humidity over 90% for much of the year, and the average maximum is over 75%. Jizan's maximum is over 90% most of the year, except between April and July, when the average maximum falls to around 80%. Dhahran's average maximum is over 80%, and relative humidity reaches 100% for most of the year. Mountainous areas such as Khamis Mushait also reach humidity levels of over 90% throughout the year with an average maximum of around 75%. Such a situation is a result of high altitude in these areas which allow for higher rainfall, hence high humidity. In desert locations such as Hail in the north and Riyadh in the interior, humidity is low, and considerable seasonal variations are common.

The number of cloudy days over most of Saudi Arabia is small. Humidity on the coast being high, clear days are fewer. A partially clear condition does little to lower temperature.

The higher the humidity in the lower atmosphere, the less is the evaporation. It is usual before dawn in coastal areas for the relative humidity to reach 100% and dew is important for sustaining halophyte grass and small bushes growing on the sand dunes.

The humidity values are often very low due to the high temperatures. However, there is considerable variation in the humidity during the year, for example, the range in values between the highest value (January) and the lowest value (June) is 33.40%. The humidity during the winter months is very high due to the rainfall, reduced evaporation and low temperatures.

Long periods of daylight during the summer, and an absence of clouds during the day, mean that solar radiation during the day, and ground radiation during the night, are intense.

2.5.3 Evaporation in Saudi Arabia

Evaporation is the physical process of water molecules moving from the liquid phase (water) to the gaseous phase (water vapour). The process is endothermic, and requires an input of thermal energy. Above any body of water, water molecules in the gaseous phase are in dynamic equilibrium with those below in the liquid phase. Water vapour pressure is the gas pressure of the water vapour above the water surface, and is a measure of the dynamic equilibrium between molecules of the liquid phase escaping the surface of the water into the atmosphere, and molecules of the gaseous phase returning to the surface.

For evaporation to continue, the water vapour above the water surface needs to be removed (requiring an input of mechanical energy, i.e. wind). This reduces the water vapour pressure above the water surface, and thereby destabilises the dynamic equilibrium. Provided that there is a source of thermal energy, water will continue to evaporate from the water surface until equilibrium is regained. Evaporation can take place faster both when the water vapour pressure is increased, and when the rate of water vapour removal is increased.

Rate of evaporation gives a measure of potential for the climatic environment to evaporate water, and is widely used as an index of soil evaporation and transpiration. This rate may remain theoretical in places where there is no water or moisture to evaporate. Pan evaporation is the measure of daily evaporation from a free water surface.

The greater part of the annual precipitation of Saudi Arabia is lost through evaporation. Such losses form an important factor in the evaluation of the water resources and the calculation of the water balance. The climatic factors affecting evaporation are: solar radiation, temperature, wind, soil water source and vegetation cover. The source of the energy available to provide the latent heat for the process of evaporation is solar radiation. Wind enhances evaporation from low lying, open, largely unvegetated and wind swept terrains. The meteorological elements of temperature, humidity, radiation and wind, indicate a high evaporation potential in Saudi Arabia (MAW, 1991).

Evaporation in reality takes place from both surficial open water bodies and also from vegetated and unvegetated surfaces: the process is known as evapo-transpiration. This is defined as the amount of water lost from both vegetated and bare ground surfaces under normal climatic conditions. The value is difficult to determine in arid environments because it is greatly influenced by soil characteristics and moisture content.

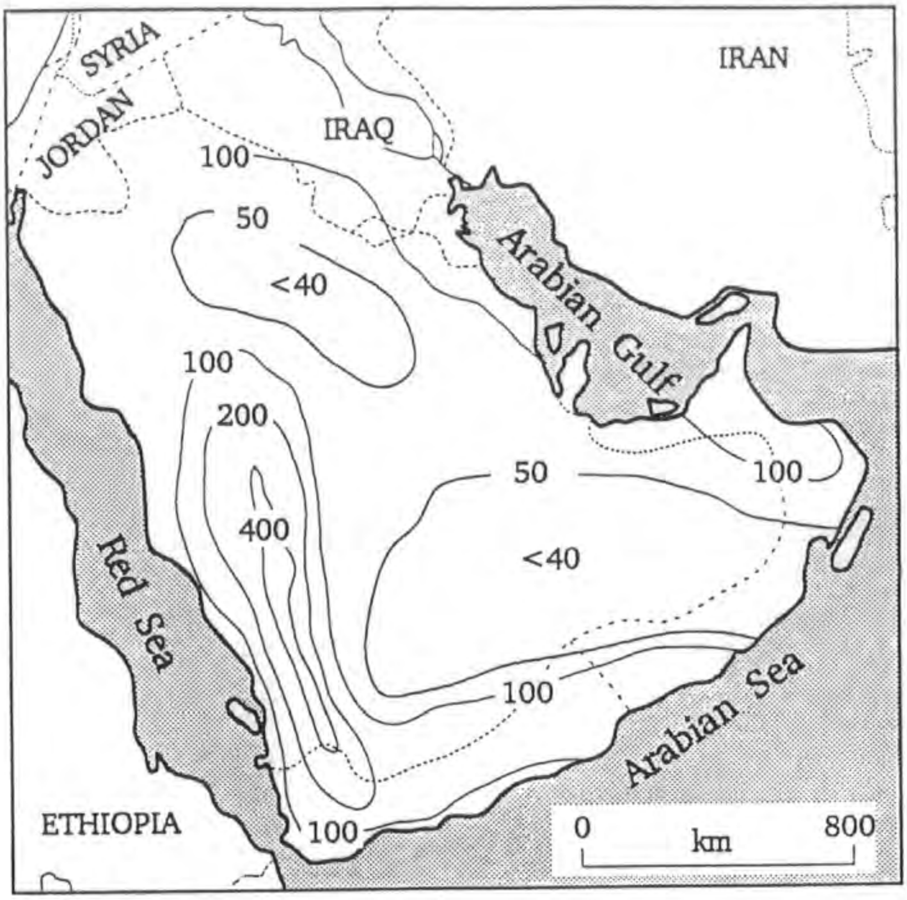
The hot, dry climate of Saudi Arabia inevitably entails a high rate of potential evaporation from land surfaces in the region. The highest potential evaporation rate usually occurs in summer, peaking in July. Winter has the lowest rate, especially in December. Annual potential evaporation varies throughout the country: it is 3,750 mm in Al-Kharj in the central part of the country; and 5,440 mm in Az Zilfi in the north, due in part to local winds.

Actual evaporation depends not only on temperature and wind speed, but also on the depth of precipitation. The reasons for this apparent paradox may be explained in considering the effects of humidity on the radiation balance and efficiency of conversion of that vapour. In addition, the efficiency with which heat is converted into vapour pressure at heat air temperatures is usually approximately constant up to mean air temperatures of 25-30°C, but sharply decreases at higher temperatures. The net effect of very high mean air temperatures of 30°C, and over and very low relative humidity of less than 15% appears, therefore, to have the effect of keeping evaporation at a fairly constant level in such conditions.

In Saudi Arabia, hot advective winds provide both thermal and mechanical energy leading to high rates of potential and actual evaporation. There are two limiting factors to the rate of evaporation. The relative humidity of the air can be great, especially on the coast, although it varies considerably in terms of location and season. Being an arid place, the interior of Saudi Arabia suffers from high rates of evaporation only where there is water to evaporate.

Evaporation studies have been conducted in various areas of Saudi Arabia. In the west, evaporation is low along the coastal lands. It remains low as one moves to the higher elevations along the escarpment, but increases eastward along the interior. Despite the differences of nearly 10°C in air temperature between coastal lowlands and the mountainous areas, the combination of these features provides for high evaporation rates. A moderate increase in evaporation can be expected southward into Rub-al-Khali area. Evaporation rates along the Arabian Gulf coast are lower. For example, at Qatif the evaporation rates are amongst the lowest in Saudi Arabia. Although air temperatures are generally in the higher range, high humidities reduce the potential for evaporation. One effect of the high temperatures is very high levels of evaporation throughout most of Saudi Arabia. The calculated open surface evaporation values are between 1,200 to 3,000mm per annum across much of the country, as shown in Figures 2.11 (a, b). Near the coasts of the Red Sea and the Arabian Gulf evaporation is 100mm; over the mountains it ranges between 20mm and 40mm; in the Saudi interior, it reaches 40mm, which is attributed to the local winds. However, there is a close relationship between the curves for solar radiation and evaporation. The evaporation rate is usually high in the summer reaching its peak in July. Over the

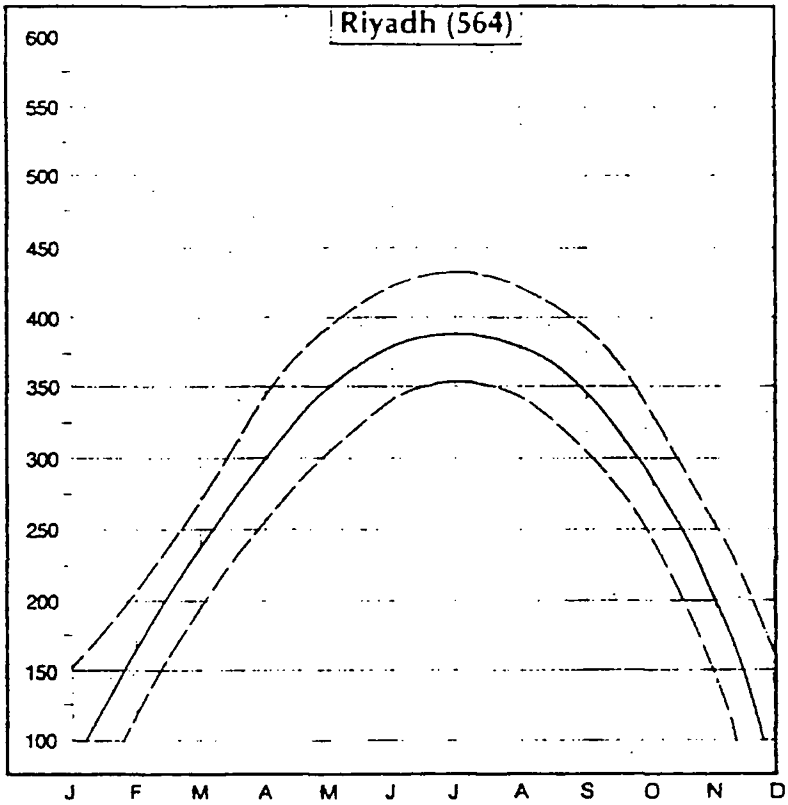
Figure 2.11a: *Annual mean average of potential evaporation*



Reference:
The Ministry of Agriculyure & water (MAW) 1987

Figure 2.11b: Mean monthly pan evaporation (mm)

Accumulative Mean Monthly Pan Evaporation in Millimeters:
Computed from Integrated Monthly Values at inland stations in Saudi Arabia



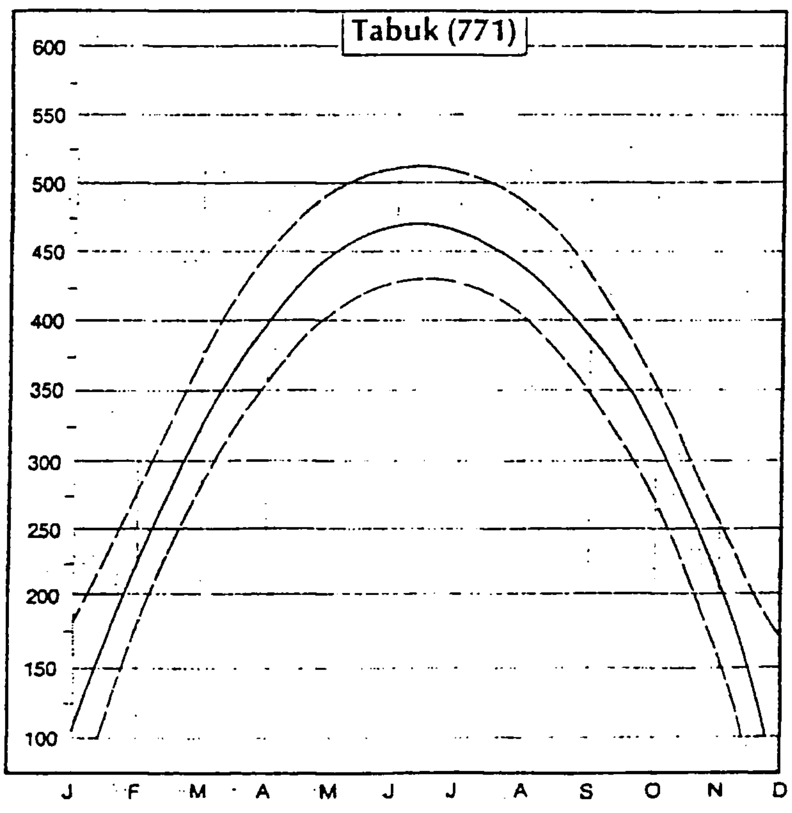
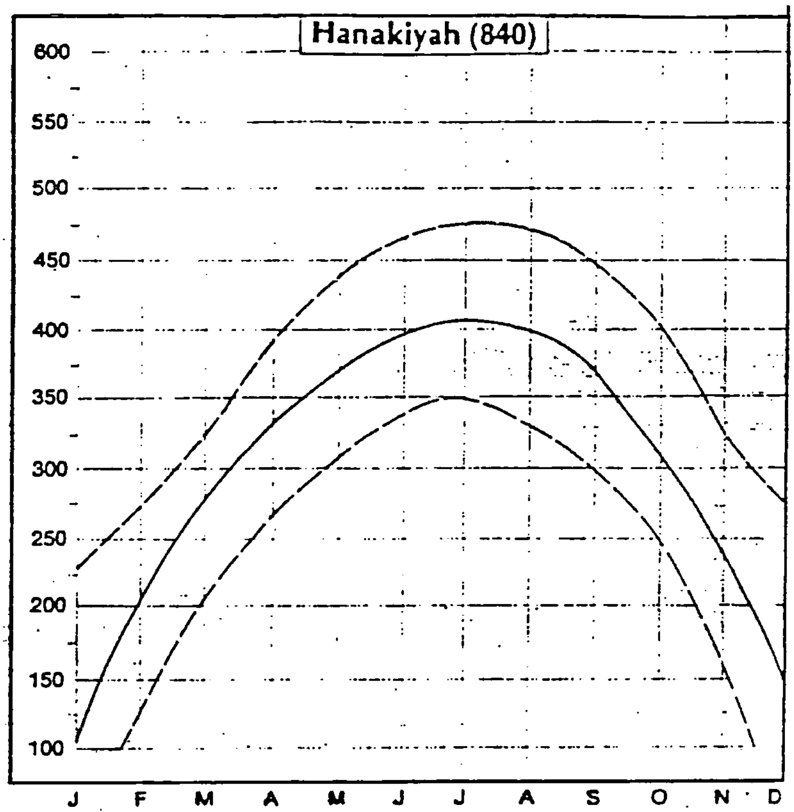


Figure 2.11b: (Continued)



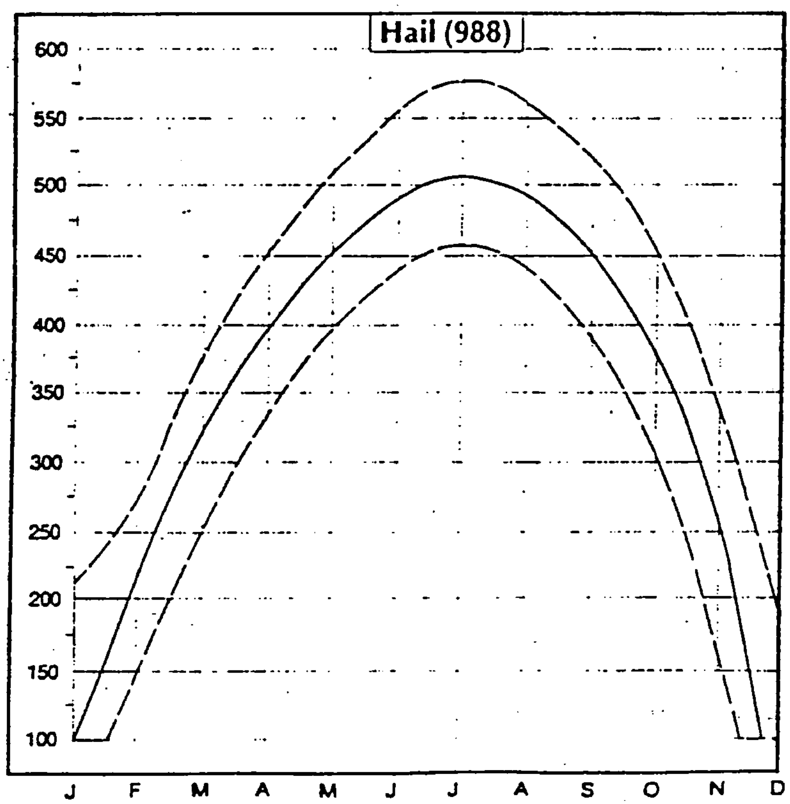
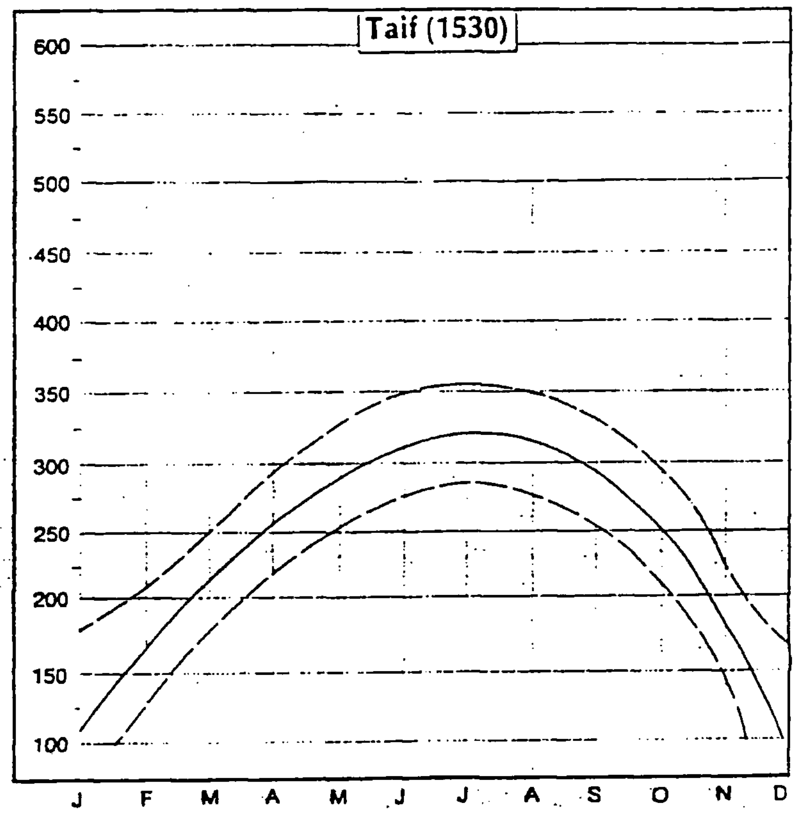
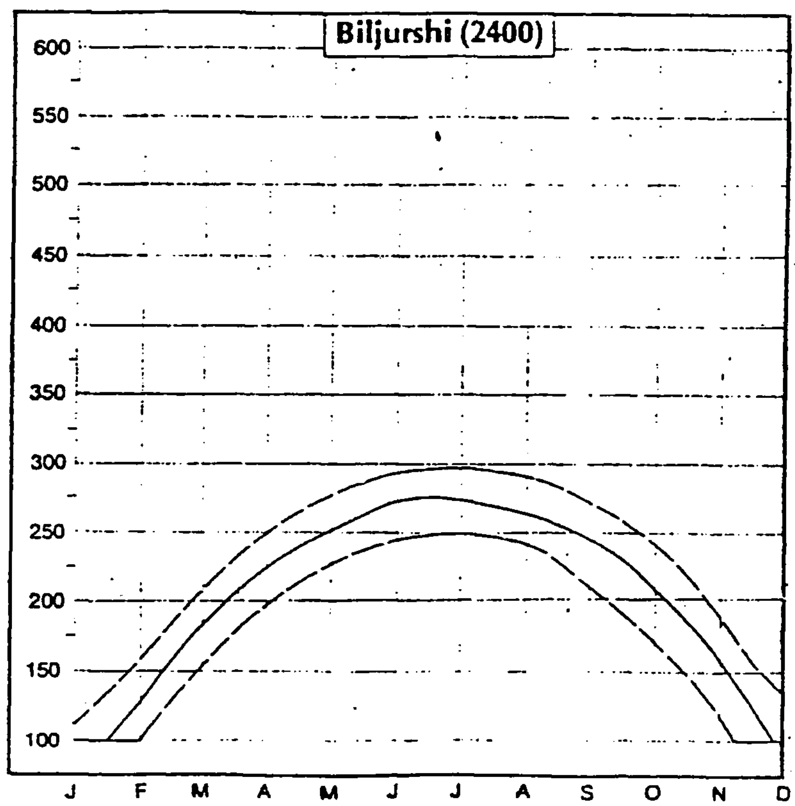


Figure 2.11b: (Continued)





highlands, the rate reaches 400mm. The mean monthly evaporation increases in summer about 300mm from open water surface. This is due to hot, dry winds, cloudless skies, and low relative humidity. The low evaporation during winter results from the relatively short days, predominantly cold winds, cloudiness and high relative humidity. Figure 2.11b gives monthly values for some cities in Saudi Arabia, the maximum peaking in the summer months (from May to October), with the highest cumulative monthly mean of July, at about 570 mm (June-July) at Ha'il, Tabouk and Hanakisah where the highest temperatures in Saudi Arabia occur, with an evaporation rate of 520-470 mm, and Riyadh is 440 mm. These cities are in hot regions. In winter in other areas, such as Bi'jurshi and Taif mountain cities, the rate of evaporation is much lower, at 290 mm, although 360 mm in summer. They give a range of evaporation which is related to variations in altitude and temperature.

2.5.4 Rainfall in Saudi Arabia

With the exception of the southwestern portion of the country, Saudi Arabia is one of the driest countries in the world. Overall, the average annual precipitation in the nation is less than 100mm. Southwest Saudi Arabia is comparatively humid and for that reason, government policy favours this area for agricultural development. In addition to sufficient precipitation, the region has rich soils and moderate temperatures. Given that this has been an agricultural area for centuries, the inhabitants of this zone have agricultural skills and the desire to remain in agriculture (MAW).

Rainfall is the only source of fresh water available for recharge over most of the country and is confined to the cool months; the only exceptions are the mountains of Asir and southern Hijaz, the southern shores of the Red Sea and possibly the southern borders of the Rub-al-Khali which experience a monsoon rainfall regime. Arid conditions persist over much of the country with the mean annual rainfall being 85.5mm if the Asir and southern Hijaz are omitted. In the mountain masses in summer and where the orographic rainfall associated with winds dominates during the cool season, the mean annual rainfall is 319.2mm (MAW).

During the winter months the eastern and north-eastern regions of Saudi Arabia may come under the influence of the Asiatic anticyclone. In this case it is likely that a tongue of high pressure dominates over the central deserts of Saudi Arabia. This local centre of high pressure may block easy penetration of the Mediterranean depressions into major parts of the country. However, during the breakdown of this anti-cyclone system, migrating depressions from the Atlantic Ocean may travel along the Mediterranean low pressure trough and may invade the country during the period of October-May. The rainfall which occurs during the winter months is obviously produced by the depressions which invade Saudi Arabia from the Mediterranean.

The Mediterranean-type depressions normally follow a west to east path across the northern region of the country in early autumn, and the associated cold front may give rain in the northern province as early as October. In November, when the Asian anti-cyclone has not developed fully, and in early spring, as the anti-cyclone recedes, frontal activity accompanied by widespread rain reaches its maximum. However, the Mediterranean moist air loses much of its moisture over land prior to reaching Saudi Arabia while its relative humidity is lowered by latitudinal heating as the moist air moves southwards. During the summer season the belt of the depressions shifts northward with the sun, the Mediterranean low pressure trough disappears, and the rain-bearing winds from the Atlantic pass to the north of the country, in this season the only part of Saudi Arabia to receive appreciable amounts of moisture is the south-west region which covers the Asir, Hijaz and the southern section of the coastal plain of the Red Sea (Tihama Asir). The area, during the summer, is dominated by moist air coming in origin from the Indian Ocean.

The annual rainfall pattern is similar in all the topographical regions and the only effect topography has on rainfall is in the localised increased totals in the highlands.

Light rainfall is soon soaked up by the ground, and surface water is lost to evaporation. Intense storms, by contrast, provide a far better opportunity for runoff conditions to occur which, in turn, can lead to ground water recharge conditions.

Rainfall variability in Saudi Arabia is extremely high. In the desert regions, sporadic, and sometimes very heavy, rainfall occurs in short, unpredictable intervals in highly localised areas, followed by long dry periods.

As a result, the value of an average annual precipitation difference between Al-Safaniyah and Abgaig along the eastern coast is 84 mm which is considered reliable. The influence of the Gulf appears to cause an increase in rainfall northwards along the coast. There are no marked geographical features that might also enhance the rainfall.

On the whole, there is higher rainfall in the northern and south-western parts of Saudi Arabia which receive more rain than the central and coastal areas.

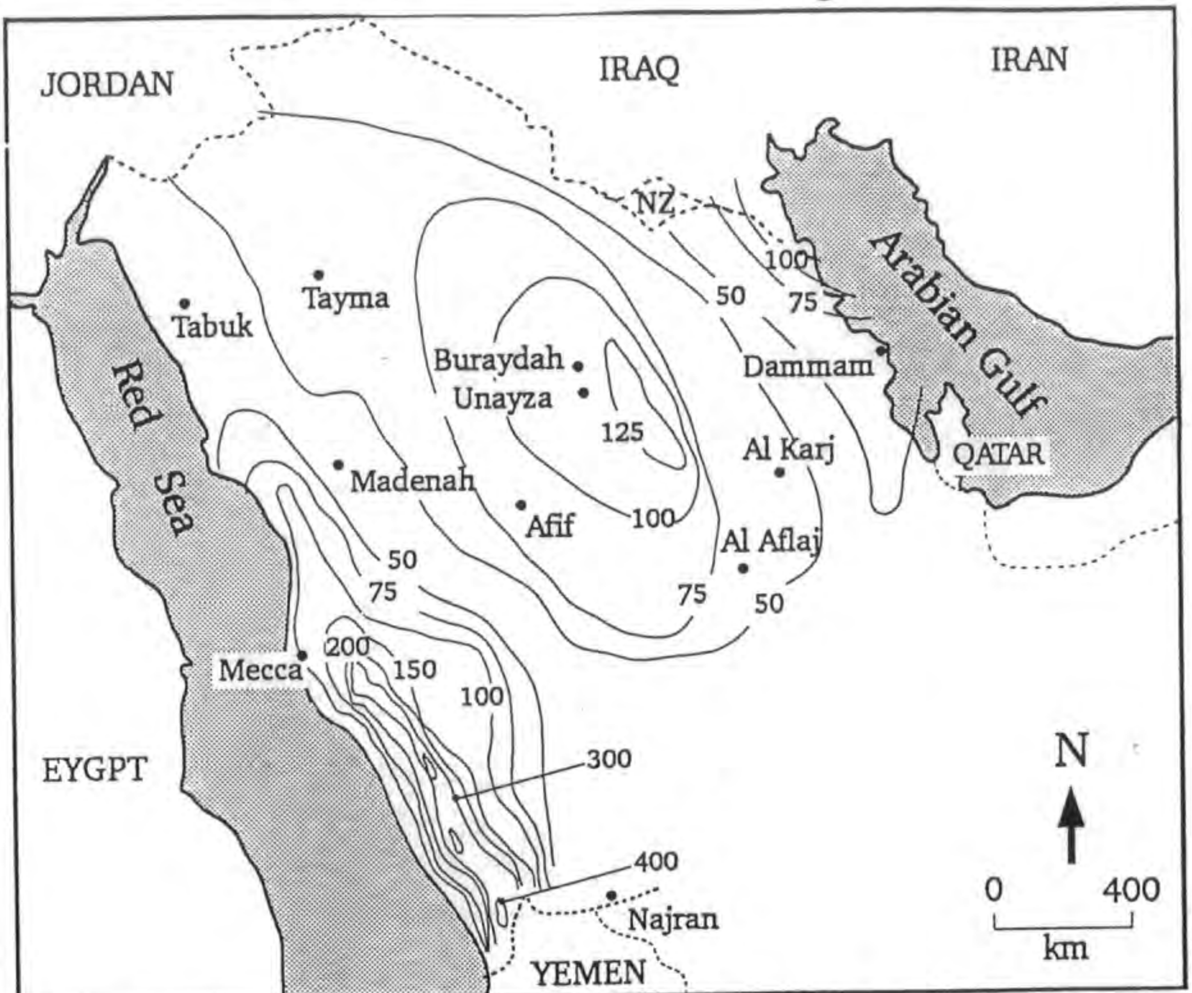
Rainfall in the Hijaz and Asir mountains is well distributed over the year, with peaks in April - May and October - November. Annual rainfall may exceed 300 mm in the mountains and averages 250 mm in Jeddah and along the southern Red Sea Coast. Rainfall diminishes as one moves north of Taif towards Aqaba. The other part which includes the Northern, Central and Eastern Provinces is characterised by low rainfall. It varies from 30 mm in the north to 90 mm in the north-east. In the Central Region, particularly around Riyadh, annual rainfall averages between 85 mm and 110 mm. The mean annual rainfall in the Asir Mountains is 1,016 mm. These rains are caused by the monsoons of the Indian Ocean. Most of the precipitation occurs during the winter months and in spring.

Annual rainfall varies between 30 mm and 60 mm in the north-west, and between 40 mm and 90 mm in the northeast. In the Central Region annual rainfall averages between 85 mm and 110 mm. In Hijaz and Asir it exceeds 300 mm in the mountain regions and equals 250 mm on average around Jeddah, but decreases northwards (MAW).

Figure 2.12 shows the zones of lower mean yearly precipitation in the great desert region of Saudi Arabia. Precipitation over Central Saudi Arabia is between 30 and 150 mm/year, and over the mountains in southern Saudi Arabia about 500 mm/year. and about 150 to more than 500 in the mountains. The mean annual rainfall increases from north (10mm) to south (150mm), from east to west, and from lowland (150mm) to mountains (500mm). Rainfall peaks occur from November to February, and from May to August. That is the monthly mean rainfall, the summer and winter rainfall respectively.

Consequently, Figure 2.12, although showing the general distribution of the amount of rainfall, is an initial figure on rainfall of Saudi Arabia. Another factor to be added on the circumstances of construction of the figure is the lack of rainfall in the north-west of Saudi Arabia and therefore the isohyets mainly show in this area the mean annual rainfall of the lower area. Furthermore, they are located in depressions within the northern Hijaz mountains and are influenced by the rain shadow of the high ranges of the mountains. In the north at Qaysumah and Yabrin in the south, the north west region and the northern section of the Red Sea coastal plain and the southwestern region which covers the southern Hijaz and Asir mountains, and also the southern section of the Red Sea coastal plain.

Figure 2.14: *Mean monthly pan evaporation (mm)*



Source: - Kingdom of Saudi Arabia Ministry of Agriculture (With Some Modifications)

2.5.5 Wind in Saudi Arabia

Wind is air movement which occurs as a result of the equalisation of differential air pressures. Differential atmospheric pressures are the result of differences in temperature. Cool air occupies a lower volume than the same mass of warm air, and is therefore denser than warm air. If warm air is cooled, its volume contracts, it becomes denser than the surrounding warm air, and sinks beneath the warm air. Conversely, if cool air is warmed, its volume expands, it becomes less dense than the surrounding cool air, and it floats above the cool air. This description applies on a local scale, and, more significantly for climate patterns, on a global scale. Air movement is the principle vehicle for patterns of climate.

The weather at any place can be affected both by air moving under the influence of huge air masses, and by winds of a more local origin. Particular parts of the world tend to be influenced by particular air masses. A locality may also experience frequent air movements specific to that location caused by features of the local environment. These more localised air movements may be sufficient to modify the local climate, soils or vegetation. Some local winds can have a profound effect, such as the funnelling of moist air up a valley on a windward slope resulting in abnormally high precipitation. A host of regional influences act to modify the general climatic pattern.

There are three predominant winds in Saudi Arabia: the north west winds, the south east monsoon, and the south west monsoon. The north west winds prevail over the whole country, with the exception of the Asir mountains and the southern section of the Red Sea coastal plain, during the period June to September. During the summer, a ridge of high pressure normally extends from the Azores eastward to cover most of the Mediterranean area. Over north west India, on the other hand, a low pressure trough develops and extends westward over southern Iran and the Arabian Gulf. This pressure pattern causes persistent north west winds to blow from the Mediterranean and North Africa high pressure area in a south easterly direction towards the low pressure area. The direction of the winds is affected by the local area. In the west of the country, the winds sweep from the subtropical anticyclone of the Azores and enter the Red Sea trench as northerly winds. In the eastern regions, the north west winds are rarely interrupted during the summer months. In the northern region, the wind direction is affected by the proximity of the area to the Mediterranean Basin. The wind direction throughout the summer months is variable between west and west north west.

During the winter - October to May - the wind direction is affected by the high pressure region over the Iran-Baluchisan plateau and the high pressure area over the Atlantic Ocean which, in mid-winter, extends over North Africa almost to the Red Sea. Owing to the comparatively high temperature of the water bodies bounding Saudi Arabia, a low pressure area develops over the Red Sea, the Arabian Gulf and the Arabian Sea (MAW).

The south east monsoon wind prevails during the period November- April, though it may start to make its appearance as early as October and continue as late as May. It is a persistent wind, blowing from the southerly quadrant over the southern regions of the country. This wind originates as a north east monsoon wind which blows towards the Arabian Sea from the Asian anticyclone during the winter. When the north east monsoon winds blow over the Arabian Sea, they recurve toward the west and north west and enter the southern region of the country as easterly and south easterly winds.

The south west monsoon wind prevails during the period June-August over an area covering the Asir highland and southern Hejaz mountains and the southern section of the Red Sea coastal plain as far north as Al-Confideh.

During the summer months, two high pressure areas develop over the Indian and Atlantic Ocean and extend into Central Africa and the north Arabian Sea. Wind speed influences the elevation-precipitation relationship. Rain falls with little variation over the region, but with high wind velocities the area of maximum rainfall was sometimes shifted leeward from the crest, and to the leeward, windward slopes exposed to high wind speed receive less rainfall than other areas because the wind increases the angle of inclination of the falling drops. In considering rainfall measurements and rainfall distribution, the wind speed should be determined.

Rainfall over most of Saudi Arabia is confined to the cool months when eastern and north-eastern regions fall under the influence of the Asiatic anticyclone. In this case it is likely that a tongue of high pressure dominates the central deserts of the country. This local centre of high pressure may block easy penetration of the Mediterranean depressions into major parts of Saudi Arabia resulting from low pressure systems in the Atlantic Ocean. In the summer, the Mediterranean low pressure regime, with its rain-bearing winds from the Atlantic, passes to the north of the country.

As shown in Table 2.5, the maximum wind speed for some cities in Saudi Arabia in 1987 was 18-40 knots (direction between 60° and 360°). Surface wind speeds, in knots, are for stations in all the topographical zones (for the hydrological year January-December). The strongest winds are on the north and south desert foreland, followed by the mountains and coasts. The cumulative monthly wind run, expressed in knots, varies from a maximum of between 40-50 knots to 18 knots over Saudi Arabia. The table provides examples of the characteristics of these phenomena and it can be seen that the maximum frequency of the occurrence of sand or dust storms is found to be recorded at all stations located in the eastern parts of the country. It can be also noticed that the minimum number of days with sand or dust storms is recorded during the autumn, while the maximum number of days with sand or dust storms is recorded

Table 2.5

MAXIMUM WIND SPEED (KNOTS) AND ITS DIRECTION ACOORDING TO THE METEOROLOGICAL STATIONS DURING 1990.

City Month	Sharurah	Al Baha	Qurayat	Abha	Najran	Rafhah	Ar'ar	Qaisumah	Turaif	Bisha	Al Jouf	Yanbu
Max. Speed	18	26	40	29	17	126	26	22	41	18	34	26
Jan												
Direction	60	280	250	200	110	300	290	230	270	260	280	30
Max. Speed	28	29	31	30	30	30	28	25	30	24	26	26
Feb												
Direction	180	210	290	200	250	180	320	320	120	230	320	260
Max. Speed	28	27	50	32	33	46	40	34	34	24	50	35
Mar												
Direction	350	240	300	210	300	270	310	130	260	230	320	280
Max. Speed	16	28	32	26	24	30	37	24	36	28	28	37
Apr												
Direction	300	160	300	180	240	150	340	310	90	270	90	270
Max. Speed	17	27	40	24	27	38	30	30	35	28	40	35
May												
Direction	80	120	260	80	100	180	270	270	200	240	300	250
Max. Speed	17	22	40	30	20	22	29	29	35	25	22	37
June												
Direction	90	40	290	70	10	330	260	360	290	70	260	270
Max. Speed	18	22	40	31	26	24	22	30	26	23	22	32
July												
Direction	210	360	300	40	360	330	300	330	270	100	130	270
Max. Speed	23	32	32	42	32	22	40	30	34	37	34	28
Aug												
Direction	70	360	310	360	90	320	20	320	70	50	320	40
Max. Speed	22	25	28	33	30	26	34	23	28	24	24	32
Sep												
Direction	30	100	310	50	360	180	140	140	270	90	190	280
Max. Speed	224	36	43	24	23	28	41	35	33	25	45	27
Oct												
Direction	90	260	280	50	90	150	320	120	80	80	180	220
Max. Speed	20	19	32	24	15	40	28	25	25	20	20	22
Nov												
Direction	70	100	280	210	100	300	310	320	270	130	320	270
Max. Speed	24	22	22	34	22	36	29	34	28	18	44	26
Dec												
Direction	90	190	190	210	1110	240	310	210	190	300	270	270

Continue from previous table

City / Month	Jizan	Khamis Mushait	Qaseem	Al Wajeh	Hail	Tabouk	Taif	Dhahran	Medina	Makkah	Jeddah	Riyadh
Max. Speed	20	24	22	26	24	19	24	28	22	14	25	22
Jan Direction	190	220	360	80	270	250	250	360	260	240	30	180
Max. Speed	22	24	24	28	30	25	35	28	35	32	26	31
Feb Direction	170	200	230	310	240	280	240	320	240	220	180	340
Max. Speed	21	22	25	32	44	44	44	31	22	18	28	30
Mar Direction	270	240	50	310	270	240	280	340	240	180	230	230
Max. Speed	26	18	22	34	40	28	31	29	18	18	22	40
Apr Direction	100	210	10	320	260	230	240	350	230	240	330	260
Max. Speed	35	16	40	32	27	48	30	25	22	25	30	45
May Direction	90	50	330	320	280	270	230	360	100	160	120	330
Max. Speed	28	18	23	36	22	29	27	34	18	15	26	35
June Direction	280	80	50	310	260	230	350	360	270	250	330	350
Max. Speed	27	22	28	26	17	22	30	29	18	18	26	40
July Direction	300	50	60	280	330	230	310	150	330	320	320	300
Max. Speed	60	20	40	28	20	40	45	31	20	22	26	32
Aug Direction	50	60	80	300	270	120	330	340	300	160	70	350
Max. Speed	38	20	20	26	22	22	30	25	20	20	24	28
Sep Direction	50	70	30	300	280	250	60	350	320	210	320	350
Max. Speed	20	20	30	55	27	35	22	29	20	16	22	29
Oct Direction	300	70	270	300	210	300	210	360	120	210	280	170
Max. Speed	18	12	20	30	30	28	16	22	19	14	25	25
Nov Direction	140	120	350	310	200	210	210	350	180	230	200	20
Max. Speed	17	20	20	34	31	32	32	29	17	20	26	30
Dec Direction	160	220	240	240	240	250	230	320	240	180	210	320

in spring and summer. The wind of the south-east monsoon normally ranges between 8 and 10 knots, though they may blow strongly during the period of the passage of the western depressions. When they are associated with the passage of the Mediterranean depressions, they are often laden with sand or dust particles.

In places such as Sharurah (a southern desert town), the maximum wind speed in this period was 18 knots in January to 28 knots in March; in Al-Baha (a mountain town) the maximum wind speed was 26 knots in January and 27 knots in March; in Al-Qurayat (a northern desert town) the maximum wind speeds for the same times were 40 knots and 50 knots; in Al-Dhahran (on the Arabian Gulf) the maximum was 28-31 knots, in Jeddah (Red Sea), it was 25-28 knots and in Riyadh (Central Region) the maximum was 22-30 knots.

Winds prevail over Saudi Arabia except the Asir mountains and the southern area of the Red Sea Coastal Plain. High pressure extends eastward to cover most of the Mediterranean area. On the east coast, on the other hand, low pressure develops and extends eastward over southern Iran and the Arabian Gulf. These pressure patterns causes persistent north-west winds to blow from the Mediterranean - North Africa high pressure area south-eastwards towards the low pressure area (MAW). The direction and speed of winds are affected by the local topography. In the west of Saudi Arabia the winds sweep from the sub-tropical anticyclone at Azores and enter the Red Sea trench as north winds. Winds then blow parallel to its shores and regularly blow as northerly or north-west winds in Jeddah area and west or west-north-west in Al-Wajh and Jizan area. Wind speeds on the coastal plain in the summer are low, and also low over the mountains. Generally, the western highlands act as a shelter to Red Sea coastal plains from the north-east and south-east winds which have a significant component on eastern slopes of the mountains. As shown in Table 2.6, the mean prevailing wind direction in Saudi Arabia was from north and south-southeast for the

Table 2.6

PREVAILING WIND DIRECTION - MEAN WIND SPEED (KNOTS) DURING THE YEARS 1975-1990.

Year	Wind Direction	Mean Wind Speed	Maximum Wind Speed	Minimum Wind Speed
1976	NNW	07	40	18
1977	N	07	40	20
1978	NNE	08	40	20
1979	SSE	07	45	20
1980	N	06	45	20
1981	SSE	08	50	20
1982	SSE	07	45	20
1983	N	07	58	22
1984	SSE	06	52	26
1985	SE	06	45	25
1986	N	06	38	26
1987	C	05	40	20
1988	N	06	40	20
1989	S	06	43	20
1990	S	06	40	22

Source: General Meteorological Department.

period 1973-1987. The mean speed for the period was 0.7 knots, the mean minimum speed was between 18 and 26 knots. The lowest speed recorded during this period was 18 knots. The mean maximum speed was 58 knots, mostly from the north, the mean minimum speed was 22 knots.

In the Eastern Region of Saudi Arabia, the north-west winds are rarely interrupted in the summer. They are continuous and persistent. Their remarkably high speed is a result of fluctuations in the intensity of the seasonal low pressure area over north-west India. When the low pressure deepens the north-west winds may become strong. The number of the western depressions which invade Saudi Arabia has not been investigated in detail, but over the south-west of Asia in general, the average rainfall is about 50mm a year, mainly during the period October - April. The rainfall which occurs during the winter months is obviously produced by the depressions which invade Saudi Arabia from the Mediterranean.

The Mediterranean depressions normally follow a west to east path across the northern region of the country in early autumn, and the associated cold front may give rain in the northern province as early as October. In November, when the Asian anticyclone has not developed fully, and in early spring, as the anticyclone recedes, frontal activity accompanied by widespread rain reaches it maximum. However, the Mediterranean moist air loses much of its moisture over land prior to reaching Saudi Arabia, whilst its relative humidity is lowered by latitudinal heating as the moist air moves southward. During the summer the only part of Saudi Arabia to receive appreciable amounts of moisture is the south west region and southern part of the coastal plain of the Red Sea. This area, in this season, is dominated by moist air originating from the Indian Ocean (MAW). Despite the fact that the summer rain is confined to the south west of the country, light showers may occur in the interior as far north as Riyadh and Qassim districts.

The main rainy season for the country as a whole is during the cool months, October to April. Rainfall may occur in September and May, but over most of Saudi Arabia it evaporates in the atmosphere before reaching the ground as a result of the intense heat. The rain occurs during the cool season either as a result of the western depressions mentioned previously or from convectional activities within relatively moist air which can be classified as polar air coming from the Atlantic Ocean via the Mediterranean, and tropical air coming from the Indian Ocean via the Arabian Sea.

The Mediterranean depressions occasionally retain sufficient energy for their associated cold fronts of polar air to have an effect, albeit attenuated, on the country, but the major part of Saudi Arabia lies in a region of warm subsiding air as previously indicated. The possibility of widespread winter rain is less because the upper air subsidence inhibit convection and causes a reduction in rainfall (MAW). Most of the winter rain, which is more widespread than that of the other seasons, has its origins in the western depressions and is therefore cyclonic in nature. This indicates that most of the rain received in Saudi Arabia is cyclonic. In fact, if a line is drawn from Salwa on the coastal plain of the Arabian Gulf to Jeddah on the coastal plain of the Red Sea, it will be seen that the areas north of this line receive 40-70% of their annual precipitation during the winter months (December to February). Western stations with heavier annual precipitation, and coastal stations with a more pronounced local effect as a result of the proximity to the water bodies, have longer lasting rains. In the interior, cyclonic rains are of short duration. At Riyadh, Unayzah and Hail, the average period of rainfall on any one day hardly exceeds 4 hours, though the cyclonic rains of winter can be persistent, and soft drizzly rain may continue to fall for one to two days when there is a depression covering the country.

Convectional rain occurs mostly in spring when longer days and bright sunshine produce considerable heat over the ground surface and result in expansion and rising of the adjoining air layer. Convection is greater in the western highlands where solar radiation is more intense than the lower areas, and where there is great emissivity of the basalt flows of dark colour and the other kinds of pre-Cambrian rocks. On the other hand, in the upper layers of air, colder temperatures still prevail, with the result that when moist air from near the surface rises due to heating and expansion, condensation can take place at comparatively low altitudes above the ground. Thunderstorms and hail are typical convectional precipitation and are common to most of Saudi Arabia in spring and summer, particularly in the western highlands as well as Tuwayq mountains and Shammar Jabals.

Convectional rainfall is of short duration, but it can be exceptionally violent and disastrous on occasions. It occurs mainly in the afternoons or early in the evenings on the days when the morning temperatures rise to higher levels than the average and when there are incursions of relatively moist air from either the Mediterranean Sea or from the Arabian Sea. It sometimes changes to hailstorms which are more dangerous to humans and plant. The hailstorms are sometimes accompanied by thunderbolts which sometimes kill people and animals.

Relief of the land becomes important where a range lies in the path of moist winds. The parallel ridges of the western highlands with a general northwest-southwest trend, are in the path of the moist winds which blow from the Arabian Sea as the south-east monsoon of the cool season or as the south-west monsoon of the summer months. They are also in the path of the moist north winds which blow from the Mediterranean via the Red Sea during the cool season.

2.6 Climate in Tihama Asir

The climate of the Tihama Asir is determined by an interaction between local air circulation due to the topography of the region, and the general air circulation over

Saudi Arabia. The influence of the air on the climate of the Arabian Peninsula varies between seasons as a result of the variation in the pressure gradient between high and low pressure regions over and around the areas. Accordingly, the climate also varies between seasons.

Hydro-meteorological networks that consist of measuring stations of rainfall, air temperature and solar radiation, relative humidity, pan-evaporation, and wind speed, have recently been strengthened in the country. The area experiences two basic climatic seasons (MAW).

In winter (December to February) the region is under the influence of northerly air flows. The region is affected by westerly Mediterranean air associated with depressions that move across northern Arabia.

During the summer (June to August), the flow pattern is well defined. The south west monsoon flows from the equatorial region into the interior of southern Asia. North westerlies prevail over the north Arabian Peninsula and merge with the south west monsoon along an extended confluence zone over the Gulf of Aden and the southern Arabian Gulf. In summer, the area comes under the influence of a moist southwesterly air flow which brings precipitation to the Tihama Asir, when the weather becomes hot and humid.

Therefore, the climate of the Tihama Asir varies from one season to another as a result of the combination of local and general circulation.

The climate of Tihama Asir is complex because of the altitudal variant which the mountains and Tihama add to a climatically little understood part of the world. The region itself is not distinctly under the influence of any one of the major global climatic regions and it is only marginally influenced by such regions as the Mediterranean winter depressions, the south westerly summer monsoon, the Inter-tropical Convergence Zone and also by the Central Asian high and low pressure cells. It is often lost between the desertic dry climate in the north east and the semi-arid monsoonal climate in the Yemen.

The climate of that part of Tihama lying south of Jeddah is tropical to sub-tropical, and much influenced by the effect of high mountains. There are two main seasons, monsoon rains with a sharp but highly variable peak in July-August, and winter rains with a much smaller but more regular peak in January, though rains can occur in almost any month of the year. The average annual rainfall diminishes noticeably in any direction away from the region. In the mountainous region, rainfall ranges between 250mm and 600mm, and on the coast between 50mm and 250mm (MAW).

Table 2.7 summarises climatic factors for Malaki (Wadi Jizan) and Sabya, in the Tihama Asir area. As shown, the climate of this area is moderate, indicating the least range of seasonal and daily fluctuations of various climatic factors in the Tihama region. Rain falls, more or less, almost every month but predominantly in spring and summer. Maximum values of pan-evaporation and solar radiation, both of which are closely related, are rather low. The daily range of relative humidity, difference between maximum and minimum, is almost constant, with fluctuations of some 50% throughout the year.

Table 2.7:
Climatic Factors in Tihama Asir

Station in the area	Malaki (Wadi Jizan)	Sabiya
Temperature (°C)		
Annual mean	30.6	30.8
Annual range	9.4	8.3
Monthly range max.	12.2 (Oct.)	12.8 (Apr.)
Relative humidity (%)		
Range min.	56	65
Monthly max	62 (Oct.)	57 (Apr.)
Annual Mean	45 (July)	44 (July)
Pan evaporation (mm)		
Annual	3.639	3.784
Monthly max.	402 (May)	426 (July)
Solar radiation ($g.cal/cm^2/day$)		
Annual mean	528	434
Monthly max.	601 (May)	559 (Apr)
Wind speed (km/h)		
Annual mean	7.5	8.3
Monthly max.	9.0 (July)	11.2 (July)
Annual rainfall		
Average mm wettest month	269 (Nov.)	112 (Nov.)

The relative humidity ranges between minimum and maximum levels in the same area: 56% and 62%, and between 65% and 57% in the same season. The annual mean in July at Malaki is 45% and at Sabya is 44% with a high average temperature and humidity. Temperatures are as a rule very high, with peaks of about 48°C and minimum levels of some 15°C. Relative humidity is always very high.

The following facts are of note:

(1) Precipitation in coastal areas occurs twice a year, because the rainfall over the Asir mountains is in the summer and winter. In open waters there are two peaks: August and November. In coastal waters the peaks are in March and May.

(2) The rate of evaporation is highest in summer, reaching its maximum in July.

(3) The long term mean rainfall is well correlated with temperature and humidity and shows corresponding peaks in April, July and November typical of spring, summer and winter rain visiting the area.

(4) The east-west transport which is governed by local Red Sea influence is characterised by:

    (a) A peak in evaporation in spring and summer for open and coastal waters.

    (b) A peak in potential precipitation in spring and summer.

    (c) Prevailing southwesterly winds towards Asir during both spring and summer.

2.6.1 Radiation and temperature in Tihama Asir

Tihama Asir is hot in summer and warm in winter. Table 2.8 shows the average summer (40°C) and the average winter temperature (35°C), over a period of 11 years, from 1979 to 1991. The great seasonal range is due particularly to the high temperature of midday summer and the extreme warmth of winter nights of this area near the coast of the Red Sea. The table, which summarises temperature at Jizan station in Tihama Asir between 1979 to 1991, can be divided into two temperature ranges, winter and summer. During the winter months from December to March, average

Table 2.8
AVERAGE TEMPERATURE (°C) OF TIHAMA ASIR FOR THE YEARS 1979-19991.

Years	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	AVERAGE
1978	33.6	35.6	38.5	41.3	43.6	44.8	43.1	41.4	43.7	43.0	38.0	36.0	40.0
1979	35.0	35.3	38.8	45.0	42.7	45.0	43.2	43.0	43.0	41.0	39.2	35.0	40.0
1980	32.1	32.1	35.4	37.8	39.8	40.0	41.1	41.1	41.1	40.1	39.2	34.0	37.8
1981	30.8	31.4	33.4	35.7	36.8	38.5	39.4	39.4	39.4	38.4	36.4	32.9	36.0
1982	30.9	32.3	34.5	36.5	37.6	39.2	39.4	39.4	40.1	40.0	38.2	35.0	36.9
1983	33.6	35.6	38.5	41.3	43.6	44.8	43.1	41.1	43.7	43.0	38.0	36.0	40.0
1984	35.2	35.2	38.7	45.0	42.5	45.0	43.4	43.0	43.5	41.3	38.4	35.6	40.5
1985	32.4	34.4	35.6	37.9	39.8	40.2	41.4	41.4	41.1	40.2	39.3	34.0	38.0
1986	30.6	32.1	34.5	36.5	37.6	39.2	39.4	39.4	40.2	40.1	38.2	35.2	36.9
1987	30.7	31.4	33.2	35.9	36.9	38.3	39.1	39.1	39.1	38.1	36.1	32.9	35.9
1988	30.9	31.5	33.3	35.6	36.6	38.5	39.4	39.5	39.5	38.4	38.4	32.9	39.5
1989	32.3	33.5	35.9	39.0	40.0	41.2	41.1	41.0	41.3	40.3	38.0	34.5	38.3
1990	30.6	32.2	34.5	40.0	41.1	42.3	42.1	42.0	41.0	40.0	36.0	36.0	38.1
1991	35.0	35.6	38.5	41.3	42.7	45.0	42.1	43.0	43.0	40.1	36.4	36.0	39.9

Source: General Meteorological Department.

temperatures are between 30°C to 38°C, and during the summer months, from April to November, average temperatures are between 38°C to 43°C. The annual average temperature was 38.3°C. Hot months are April to October, the hottest months being June and September, and thus representing summer temperature. The cold period is usually shorter: from December to January, with January the coldest month, and thus representing winter temperature (MAW).

The Red Sea is considered to have a major effect on air temperature over the land in close proximity. Most of the area remains hot throughout the year. The temperature trend in the Tihama Asir is from north-west to south-east. Consequently, there are constant south-east north-west gradients of mean annual air temperature as a result of the effect of the latitudinal factor.

The annual range of temperature is defined as the difference between the mean temperature of the warmest month and that of the coldest month. The annual range of temperatures increases with increasing latitude because of the greater difference between winter and summer insolation as the distance from the equator becomes greater. The distance from the Red Sea is another factor that influences the annual range of temperature.

(1) Summer

Summer is the longer season lasting from late May to October. Daily temperatures may reach from 36°C to 37°C, with an absolute maximum temperature in these months reaching 40°C to 44°C and the nights remain at the same average (15°C-20°C). The rays of the noonday sun, beating down on barren areas make the sand and dust storms very hot because the sun is at its northernmost range causing intense solar radiation, which in turn causes temperatures to be very high during the afternoon.

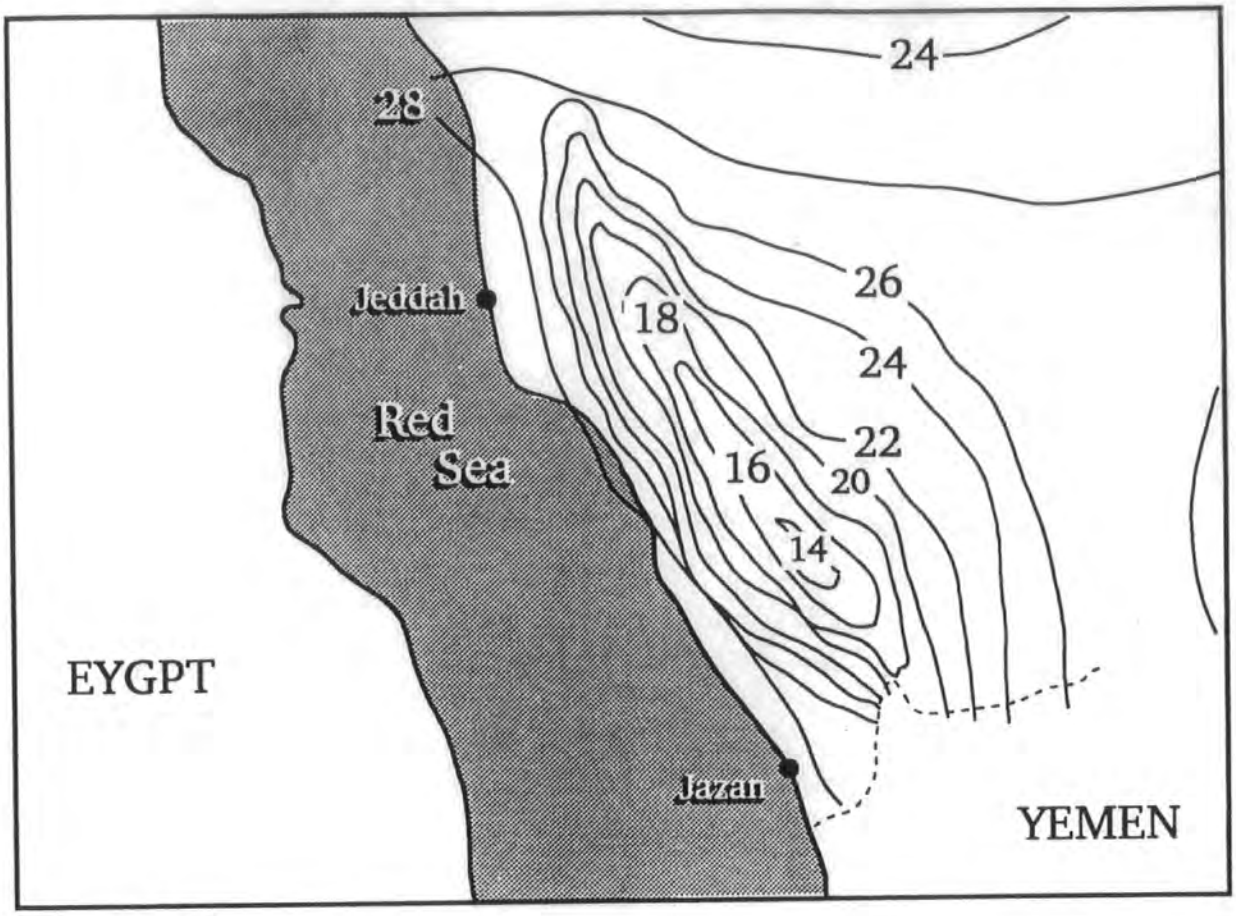
(2) Winter

Winter lasts from December to February. The average temperature varies from 33°C to 36.9°C. The great seasonal range is due particularly to the high temperature of midday summer and the extreme warmth of winter nights. Since the littoral area extends from the south-east toward the north-west, air temperature decreases in this direction. The mean temperature of the winter months is constantly over 15°C at all the climatic stations located in Tihama Asir. At Jizan, the mean monthly air temperature during the winter ranges between 23°C in January and 25°C in December. The winter is cool to warm and humid.

The mean monthly temperature ranges from 29°C to 30°C with a minimum of 33°C. Hot months are April to September with July being the hottest month and thus representing summer temperatures. The cold period is usually shorter, from December to February, with January being the coldest month and thus representing winter temperatures. The temperature is different with the differences in elevation, as found in Figure 2.13 which gives a mean annual temperature of 15°C at Abha in the Asir Mountains, and 25°C at Abu Arish. At Jizan on the Red Sea coast it is 20°C. The mean annual temperature distribution is found the lowest over Asir Mountain and the highest annual temperature is near the coastal areas.

The Figure shows the distribution of the mean annual temperature over Tihama Asir. The west-east temperature gradients as a result of the increases in elevation are easily noticeable. The mean annual temperature for the period of records, for the mountains situated in the south west of Saudi Arabia, show that their temperatures are ameliorated during both seasons by their proximity to both the Red Sea and the Arabian Sea waters.

Figure 2.13: Tihama Asir mean annual temperature



Source: MAW

The Red Sea is considered to have a major effect on air temperature over the land in close proximity to the sea, and almost the entire coastal area remains hot throughout the year. The coastal plain slopes towards the Red Sea from the north west. Consequently, there is constant southwest gradient of mean annual air temperature as a result of the effect of the latitudinal factor. The mean annual temperature at Jizan (12°N) on the Red Sea coastal plain is 20°C, but the mean monthly temperature is between 20°C and 25°C over the major part of Tihama Asir.

2.6.2 Relative Humidity in Tihama Asir

Relative humidity increases from the eastern part of the plain to the west. The mean annual relative humidity in Jizan is found to be 97-99%. On the coast the highest is 60-70% in winter (December to March) and the lowest is 73% in summer (June to August). Mean monthly and annual relative humidities vary from place to place, and they also change from year to year. As a general rule, the highest values of relative humidity occur during the hours of darkness, often around dawn, in association with the lowest air temperatures of the day, whilst the lowest values of relative humidity usually occur around midday or during the afternoon, in association with the highest air temperature of the day. However, the variability is much less than for the precipitation values. Tables 2.9, 2.10 and 2.11 give the humidity in Tihama for the period 1984-1991. Lowest humidity occurs in the summer, with monthly mean values of 73% at Jizan (Malaki), 88% at Sabya and 80% at Baysh. December is the month of maximum humidity, with mean values of 100% at Jizan, Sabya and Baysh. The annual mean values are 99.8% at Jizan, 90% at Sabya and 94.2% at Baysh. The average annual percentage is found to be 99%, 90% and 82% at Jizan (Malaki), Sabya, and Baysh respectively. The mean monthly relative humidity varies from 73% to 90% at Jizan, 74% to 90% at Sabya and 80% to 90% at Baysh. The monthly average shows a

Table 2.9

MEAN RELATIVE HUMIDITY IN JIZAN (Malaki) DURING THE PERIOD 1984-1991. (%)

Years	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	AVERAGE
1984	97	97	100	97	100	100	100	100	100	100	100	100	99
1985	94	91	89	86	82	87	79	81	90	94	97	92	88.5
1986	100	100	100	100	100	99	99	98	100	100	100	100	99.8
1987	90	92	80	87	84	86	73	81	88	86	87	92	86
1988	100	100	100	100	100	99	99	98	88	86	97	92	96.6
1989	94	97	100	94	92	96	97	100	100	98	97	97	96.8
1990	98	98	97	97	100	100	100	98	96	98	97	96	97.9
1991	100	100	98	98	100	99	99	98	100	100	98	97	98.9

Source: General Meteorological Department.

Table 2.10

MEAN RELATIVE HUMIDITY IN SABYA DURING THE PERIOD 1984-1991. %

Years	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	AVERAGE
1984	95	91	89	85	94	87	100	80	86	75	98	98	75.42
1985	90	88	90	83	90	86	98	83	79	78	100	100	88.75
1986	95	90	87	85	92	85	93	82	86	77	96	96	88.7
1987	88	88	90	80	85	84	88	80	85	74	94	94	85.83
1988	90	88	90	85	94	89	100	82	86	77	100	100	90
1989	92	92	90	90	89	86	98	85	80	80	99	100	90.08
1990	95	90	89	85	92	85	88	80	85	78	98	98	88.58
1991	89	90	88	87	90	86	95	85	88	85	98	98	89.91

Source: General Meteorological Department.

Table 2.11

MEAN RELATIVE HUMIDITY IN BAYSH DURING THE PERIOD 1984-1991. %

Years	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	AVERAGE
1984	100	93	97	93	96	89	81	87	96	95	90	97	92.8
1985	96	92	85	80	82	86	84	87	84	86	80	81	82.3
1986	100	100	100	98	99	98	87	85	86	98	99	100	95.8
1987	92	92	91	89	86	80	80	85	87	99	100	100	90.1
1988	100	100	99	99	96	80	85	85	90	98	98	99	94.2
1989	98	96	89	85	87	88	85	86	84	86	82	94	87.5
1990	99	99	99	96	95	89	88	87	94	96	90	97	94.6
1991	100	99	100	98	97	98	87	86	84	99	100	100	95.6

Source: General Meteorological Department.

peak of 80% to 100% between June and August, while this measure is less than 75% for the remainder of the year.

Evaporation from the sea locally elevates humidity to high levels, and the coastal plain of Tihama tends to experience higher humidities as a result of the concentration of moisture in these areas. May is the least humid month, with the mean relative humidity being 74% in all the region. There is an abrupt increase of relative humidity in June to over 87%, persisting at that level for four months. There is usually a huge diurnal variation in relative humidity as shown in the tables. This humidity range is wider during the summer than the winter months in the area (MAW).

The maritime influence of the Red Sea does not penetrate far inland because the western mountains prevent climatic modification, and thus concentrating any maritime effects along the coastal strip. Moreover, the Red Sea is narrow and the air, when blowing across it to the coast, does not have long to recharge with sufficient moisture to modify air temperature, since the moisture rapidly diminishes inland beyond the coastal plain.

2.6.3 Evaporation in Tihama Asir

The high evaporation rate during the summer months, a consequence of high temperatures, long hours of sunshine and stiff winds, are to be expected. As a result, consumptive water use increases from winter months to summer months, particularly in the areas of domestic use and agricultural irrigation. The range of evaporation rates is related to variations in altitude and temperature.

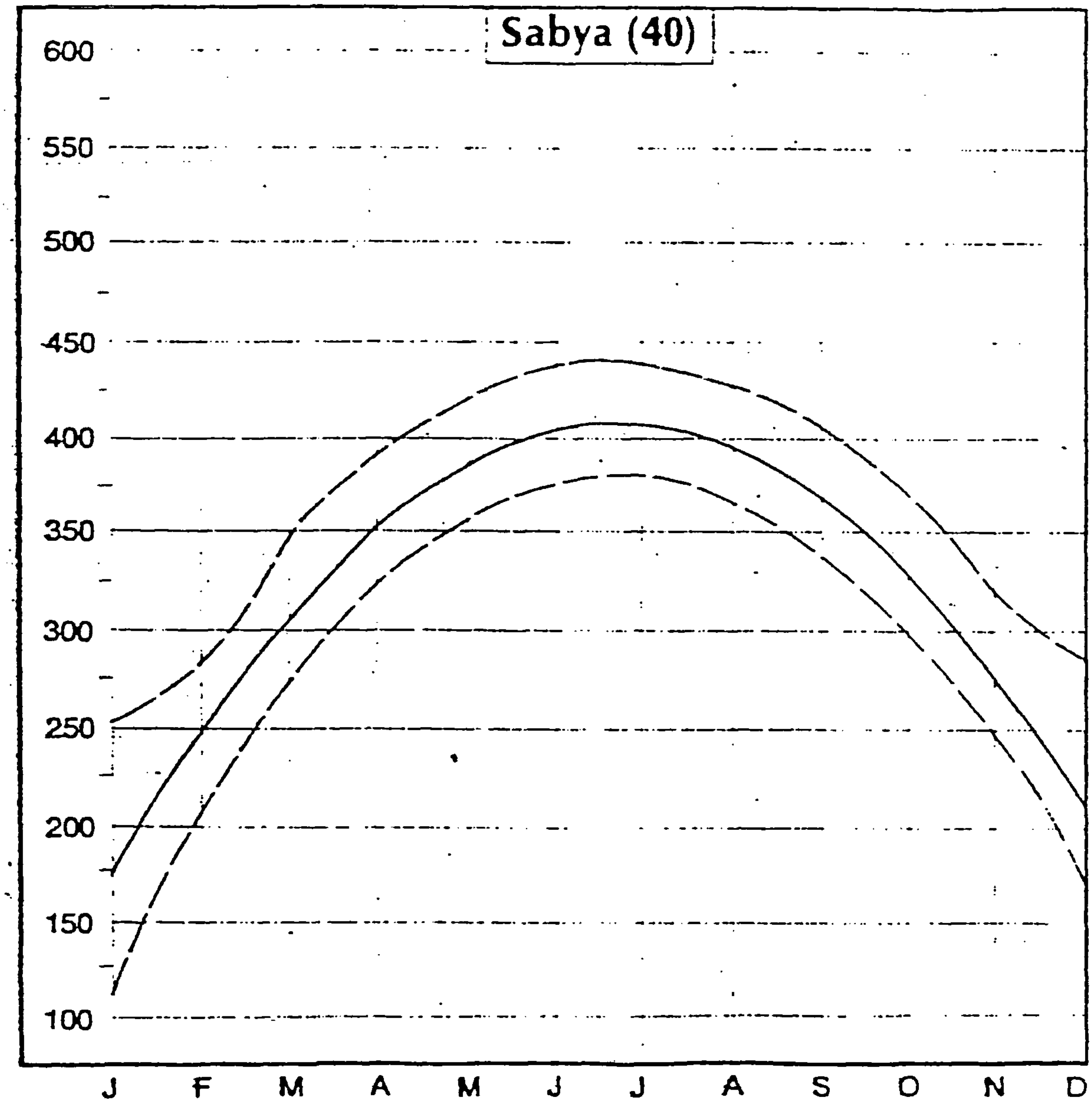
The evaporation is low along the coastal lowlands. It remains low as one moves to the higher elevations along the escarpment, but increases eastward in the interior. The magnitude differs considerably, the annual total ranging from 2,400 to 2,600 mm, despite differences of nearly 10°C in air temperature between the coastal lowlands and mountain areas, and the coastal lowlands have higher humidity than the mountain areas (MAW).

The hot, dry climate of Tihama Asir during the summer months strongly increases the evaporation rate from land surfaces in the region. The maximum evaporation rate usually occurs in the summer with its peak in July, whilst winter has the minimum rate, especially in December. The annual evaporation is about 3,608 mm, which is about 25 times its mean annual rainfall. The high evaporation rate, such as that experienced in Sabya City, is attributable to local winds. Figure 2.14 shows the distribution at monthly intervals throughout the year.The peak months are June and July, but May and August are also high. A maximum weekly average of 26.1mm/day is recorded for the week in July, and a minimum weekly average of 2.8mm/day is recorded for the week in January. The maximum monthly evaporation is 450mm in July, whilst the minimum monthly evaporation is 100mm in January. Evaporation from the Red Sea gives rise to high humidities locally. The coastal plains of Tihama Asir which is backed by the mountainous barrier of Asir highland, experience higher humidities as a result of the concentration of moisture in these areas. For example, on the Red Sea plain, Jizan's absolute maximum is over 90% most of the year, except from April to May, and the average maximum is around 80%. In mountain areas, for example, Khamis Mushait, absolute humidity reaches over 90% throughout the year with average maximum of around 75%. Such a situation is the result of high humidity.

2.6.4 Precipitation in Tihama Asir

Tihama Asir lies on the southern side of Saudi Arabia. The most important and valuable section of the wadis is the catchment area near the mountains, because of its comparatively high altitude and suitable location with respect to the Inter Tropical Front, which for part of the year brings the area under the monsoonal effect of the Indian Ocean. It is obvious that the climate of the area is governed by the movement

Figure 2.16
MEAN MONTHLY PAN EVAPORATION
Accumulative Mean Monthly Pan Evaporation in Millimeters:
Computed from Integrated Monthly Values at inland stations in Tihama Asir



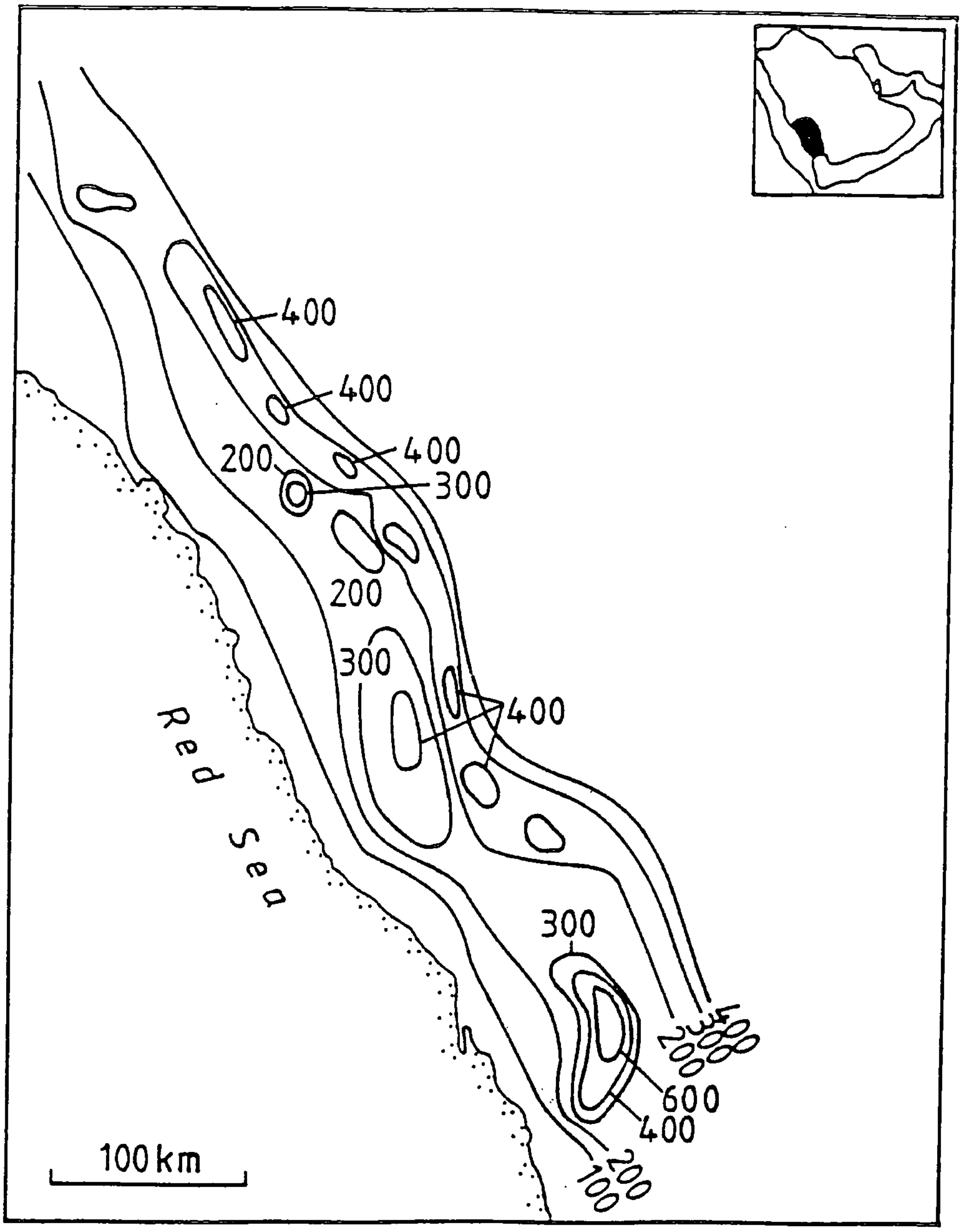
of the Inter Tropical Front and the geographical features of the area. Thus, the most abundant rainfall occurs in the Asir mountains when the edge of the monsoon extends northward into Saudi Arabia. Actually, rainfall is very irregular and concentrated in relatively short but heavy storms.

Mean annual rainfall in Saudi Arabia is 95 mm/year, but in the southwest declines from over 550-600 mm in the upper Asir Mountains, and 400 mm in Abha area, to 250 mm - 50 mm on the coastal plains. The rainy season averages given in

Figure 2.15 show similar mean annual rainfall in Tihama Asir. In the southern region over the mountains this amounts to 600 mm, and in the northern region on the coast as low as 100 mm or 200 mm. The amount of precipitation varies from one station to another, but generally increases with elevation. The Asir mountains are orientated north-west to south-east, and are therefore perpendicular to the southwest air flows. The mountains act as a barrier, and force the air to rise, cool and release their burden of water vapour. The general figure shows distribution of the amount of rainfall in Tihama Asir. It can be shown that the amount of the mean annual precipitation in the Asir mountains is higher than in the high ranges. However, the annual rainfall in the mountains of Asir is higher than in the foothills area (Tihama Asir area). The area experiences a mean annual rainfall of about 200 to 300mm. This amount increases to more than 400mm in the area from foothills to high land over the Asir mountains in the east, and the amount decreases to less than 100mm in the area from Baysh to the Red Sea. The rainy season is from July to September.

Rainfall in the area varies greatly from year to year, with an average of 13 rainy days on the plain - mainly concentrated in July and August, whilst the average number of rainy days in the mountains varies from 30 to 40 or more.

Figure 2.15: Mean annual rainfall in Tihama Asir (mm)



Rainfall may be divided into three categories: winter rains from November to January, the Mediterranean type distribution, which is due to the invasion of the polar air in the rear of depressions, predominant on the coastal plains and on the peaks which decrease towards the north; spring rains from March to May which fall only in the mountain areas; summer rains or monsoons from July to September, the typical summer monsoon type of rains when the intertropical frost moves towards the north, and humid air from the Indian Ocean is pushed by south-east winds, diverted by the Ethiopian Mountains, arrives from the east to the southern parts of Saudi Arabia, and falls as rain predominantly on the coastal plains south of Qunfudah.

Along the Red Sea coast and adjacent land, conditions vary from September to February. Along the Red Sea Coast the maximum precipitation occurs in the autumn and winter seasons. The date of maximum precipitation along the coast varies from one station to another and also from stations located near the Red Sea to stations a little further inland. For example, the date of maximum precipitation at Al Gooz (17° 8' N, 42° 27' E) is approximately on 21 November, whereas at Qahmah (18°0' N, 47° 40' E) the date of maximum precipitation is on 13 January. In addition to the variation in the date of maximum precipitation near the Red Sea, the date also varies from the Red Sea coast to the east. For example, the date of maximum precipitation at Suq Ayban (17° 19' N, 43° 2' E) is in November, and for Wadi Doqah is in December. In the east, the date of maximum precipitation occurs approximately in September and November (MAW).

The study of the rainfall characteristics of the area and their relation to the surface water is underway. The lack of an efficient network of rainfall stations and the shortage of available and continuous recorded data compelled the investigators to correlate the average rainfall and area stations.

Sogreah (1970) found that the surface water coefficient was dependent above all on the surface area affected by rainfall and that all the surface values varied between two limits accordingly. Also it appeared that there was no rule allowing the characteristics of a particular shower to be linked to those of particular run-off.

The mean annual run-off for the gauged wadis were related to the respective catchment area. The main reason for the low value of Wadi Baysh was the different rainfall distribution due to the extension of a great portion of its watershed more easterly where the precipitation is less. However, it is assumed that the long term average annual rainfall over the catchment area of the Tihama Asir is about 450 mm (MAW).

Table 2.12 shows the annual rainfall total for the period of records (1977-1991) 15 years for Wadi Baysh. The years 1977, 78, 79 have the totals of 344.9mm, 331.3mm and 375.1mm respectively, when the rainfall was heavy. In other years the rainfall was low, such as in 1981 when it was 74.7mm, 1984 when it was 75.8mm, and the lowest years in 1988 and 1988 of 62.5mm and 35.7mm respectively. It is necessary to emphasise that the area is located in the rain shadow of the Asir mountains and when the rainfall increases over the Asir mountains, it is also increased in the area. The variation in the annual value by applying the mean statistic is due to the extreme variance in the annual precipitation received by a station from one year to another.

Surface water in arid areas occurs sporadically as short isolated flow periods separated by longer periods of low or zero flow. Hence, the annual run-off coefficient is an integrated average value for a particular basin. It would be of great interest to determine daily, monthly and annual values of the surface water coefficient and study its characteristics and variations with respect to the daily, monthly and annual precipitation.

Table 2.12
MEAN MONTHLY RAINFALL (mm) IN TIHAMA ASIR (WADI BAYSH) DURING THE PERIOD 1977-1991.

Years	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	ANNUAL
1977	89.1	0	0	0	13.1	0	0	107.0	7.7	115.1	12.9	0	344.9
1978	37.5	14.2	0	0	3.1	0	158.6	16.0	39.7	52.2	0	0	331.3
1979	103.3	0	2.6	0	9.8	10.8	0.2	52.8	77.6	4.4	0	76.6	375.1
1980	4.2	7.6	0	0.6	5.0	0	3.4	28.2	37.2	0	6.2	3.4	89.8
1981	0	1.0	16.7	1.6	0	0	18.9	5.6	2.6	28.3	0	0	74.7
1982	19.2	22.8	1.6	0	26.0	0	13.1	1.7	49.2	55.8	56.8	63.8	310.0
1983	0	0	0	23.1	5.6	4.5	0	21.3	5.2	1.4	0	52.2	113.3
1984	9.0	0	0	0	40.7	0	25.3	0	0.6	0.2	0	0	75.8
1985	17.1	0	0	29.1	22.4	0	0	11.6	26.6	12.2	0	10.7	165.7
1986	1.0	0	18.9	53.6	0	0.2	13.8	14.7	19.0	4.2	0	26.4	152.4
1987	7.5	0	8.8	41.0	8.8	0	16.0	13.0	15.2	26.2	7.4	0	143.9
1988	7.8	5.8	0	9.0	0	0	16.9	8.6	14.4	0	0	0	62.5
1989	17.6	5.2	0	5.1	0	0	4.3	0	0	5.3	0	7.5	35.7
1990	0	6.1	46.2	0	14.1	0	18.1	0	5.5	0	20.3	20.3	93.3
1991	0	9.4	15.5	47.4	0	0	49.6	47.2	30.3	0	0	43.5	242.9

Source: General Meteorological Department.

There are 21 existing rainfall stations lying in the south-western part of Saudi Arabia. They are covering the wadis of Baysh, Sabya, Damad, Jizan, Khums, Khulab and Liyyah. The total area covered by these 21 stations is about 8,400 sq. km, one rainfall station representing an area of approximately 400 sq. km. by annual record. The findings shown in Table 2.13 summarise the total monthly rainfall values and number of rainy days for the selected 9 stations for the years 1977 to 1991 according to the available monthly data. Therefore, the monthly rainfall will be established using the available data during the period 1977-1989 and also gives the total annual rainfall for the selected 9 stations with their averages and the corresponding total annual inflow into area reservoirs, and the annual rainfall in Tihama Asir from 1980 to 1991 shows that the lowest rainfall was during 1980 (2329.9 mm), but the maximum rainfall was recorded in 1980 (4640.4 mm). For example, rainfall during the period 1980-1991 at Wadi Baysh in Tihama Asir and gives two divisions for annual rainfall, heavy and low rainfall in Wadi Baysh. The years 1980, 1981, 1983, 1987, 1988, 1989 and 1990 had low rainfall, but in the other years heavy rainfall occurred, between 113.3 mm to 375 mm.

Table 2.13:
Mean annual rainfall (mm) in Tihama Asir (various stations) during the period 1980-1991

Station	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Baysh	93.3	93.1	242.9	35.7	344.9	331.3	375.1	89.8	74.7	310	113.3	75.8
Abu Arish	154.9	206.8	55.9	123.7	0	315.3	0	226.8	382	582	239.3	70
Barik	386.6	690.8	598.8	399.3	332.3	459.7	442.3	279.9	388.6	432.7	102.5	158.5
Jabl Fayla	399.7	591.1	934.6	811.5	891.5	631.7	822.2	489.5	967.1	980.4	564.2	362.5
Suq Ayban	331.1	270.6	498.5	55.7	78.6	227	448.8	307.7	304.1	232	164.2	16.7
Jabal Sala	488.7	538.9	323	376.4	285.5	439.4	401.5	352.9	383.5	465	198	268.5
Ardah	310.7	197.9	351.2	0	139.7	436.4	275.5	194.7	45.2	51.2	95.2	140.4
Darb	164.9	139.4	123	103.6	127.5	111	209.4	44	13.8	17.4	93	43
Total	2329.9	2728.6	3127.9	1905.9	2200	2951.8	2974.8	1985.3	2459	3070.7	4640.4	1135.4

Source: GMD

Stations of low elevation in the area show high winter percentages. These stations gain their precipitation from the cyclones which blow in from the Mediterranean. The stations located at higher altitudes, such as Baysh, show relatively lower percentages of winter precipitation since these stations gain more convectional or orographic rainfall in the other seasons. As a general rule, the percentage value of winter precipitation on the Red Sea coastal plain decreases with increasing distance from the Mediterranean.

In the summer, precipitation represents only a low percentage of annual rainfall in the coastal strip. Summer precipitation represents 43% of annual precipitation at Darb, 75.8% at Baysh and 70% at Abu Arish.

The rainfall during the years 1980 to 1991 at Tihama Asir shows differences for total monthly rainfall between areas in Tihama such as Baysh, which had between 35.7 mm and 375.1 mm, and Barik, which in some months has between 386.6 mm to 442.3 mm. Precipitation in the area is also high: 188 mm at Abu Arish, and 655 at Jabl Fayfa.

Summer temperatures can reach 36°C monthly average and winters 24°C, thus lowering the temperature range. Humidity is always high and rainfall increases towards the south due in particular to the monsoon, the effects of which become perceptible south of Al-Lith. The average annual rainfall is 215 mm (MAW). The southern mountain region is characterised by cooler temperatures, winters are relatively cold and the average annual rainfall is over 300 mm at Abha.

Rainfall may be divided into three categories; winter rain from November to January, predominant on the coastal plain and on the peaks; spring rains from March to May which occur only in the mountain area; summer rains, or monsoon from July to September predominant on the coastal plains south of Qunfudah. Based on a period of 10 years (1981-1991) records of the average annual rainfall for four stations is as follows:

Yabha	411 mm	Zafir	522.8 mm
Bishah	176.1 mm	Biljurushi	304.5 mm

The annual average rainfall is 522.8 mm 176.1 mm in these cities. The annual value of rainfall obtained for each station is varied by using the mean statistics.

2.6.5 Winds in Tihama Asir

The most prevalent winds in Tihama Asir are the southwesterly winds which occur during the monsoon, and the northeasterly winds which occur during the winter months.

A wind prevails over the area of Hijaz and Asir mountains and the southern area of the Red Sea Coastal Plain as far north as Al-Qunfodah. The only climatic stations which record data and wind direction in the area are Jizan and Khamis Mushait in the southern area, and Taif in the northern area.

The two high pressure areas which develop over the Indian and Atlantic oceans, extend into Central Africa and the Arabian Sea. At the same time low temperatures develop over northwest India and extend westwards over the Arabian Gulf and Arabia. In these circumstances the winds blow over the area in a west to southwesterly direction. The available data on wind direction shows that this is the case, though it appears that northwestly winds form a significant component at Jizan station, which is located in the southern area of the Red Sea Coastal Plain and appears to be affected considerably by the southwest monsoon. The most frequent winds of Tihama Asir are onshore winds from the Red Sea which blow mainly from the sector between south west and west, but from west and north west in the months of May to July. Dust storms are usually sudden and violent, gusting with speeds up to 60-70 m.p.h.. Wind speed over Tihama Asir is normally gentle to moderate, with velocities ranging from 9 to 13 knots. The winds become stronger during depressions, when they blow from the north or northwest, and normally produce dust storms in the Tihama Asir area (MAW).

Visibility is reduced in the southwestern region of Saudi Arabia when dust and sand storms occur. These deepen troughs (areas of low atmospheric pressure) and produce associated frontal activities across southern Arabia. Unless there has been rain, further deterioration of visibility may occur with higher wind speeds. Dust storms in Tihama Asir blow in from the north, and are associated with the approach of a depression. The dust storm precedes heavy rain on the plain and adjacent hills and Asir mountains.

2.7 Vegetation

Factors that determine the vegetative cover of the earth are of prime concern to the geographer. The various plant associations owe their nature to the interaction between climatic elements such as heat, light, moisture and wind, as well as other features such as surface relief and soil cover. These conditions impart a special character and a distinctive appearance to a particular association of plants. It is possible to distinguish areas of the world which have broadly similar plant associations, termed *vegetation regions*.

The principle of description of vegetation is in terms of its structure, and the organisation of vegetation into plant assemblages of various orders of magnitude. However, the most distinct feature in this respect is a recognisable vegetational region; exhibiting features that differ from all surrounding country. The first visible contrast is that the vegetational cover in the highlands tends to be denser, taller and greener than that of neighbour regions.

2.7.1 Vegetation in Saudi Arabia

The two main elements on which plant growth depends are rainfall and temperature, and particularly the seasonality of these elements.

In a broad sense, rainfall determines the vegetation type: abundant rainfall tends to produce forest; light rainfall, grassland; and meagre rainfall, scrub and desert. However, water from rainfall is not always available as soil water to plants, due perhaps to rapid run-off or high rates of evaporation. In contrast, the soils in other place may retain sufficient water for plants to use over ensuing periods of drought. Therefore, much depends on the water-retaining properties of the soil (Monkhouse, 1986).

Every type of plant has a maximum and minimum temperature within which range plant growth is normal, and also a maximum and minimum temperature outside which range the plant cannot survive. The impact of other factors, such as the intensity of light, or the air humidity, combined with high or low temperatures can have a profound effect on a plant. The indirect effects of temperature may be extremely important to plants, affecting for instance the rate of evaporation of near-surface soil water, or the rate of absorption of soil water by roots.

The amount and intensity of light varies from time to time in accordance with latitude, season, local relief, climatic factors (such as cloud cover), and with the proximity of other plants. Leafy layers may occur in vegetation at various heights. For some full-grown plants a specific height above the ground may meet their light requirements which may be quite different for plants above and beneath them (Al-Sharif, 1977).

Air movement affects the rate of evaporation and temperature of a plant, depending on the vigour of the movement (as well as the relative humidity and temperature of the air). In some plant organs which experience rapid transpiration, processes may occur which cause the plant to grow more strongly on the leeward side. Wind can also have an indirect impact on vegetation by drying out a soil, and therefore reducing the availability of soil water.

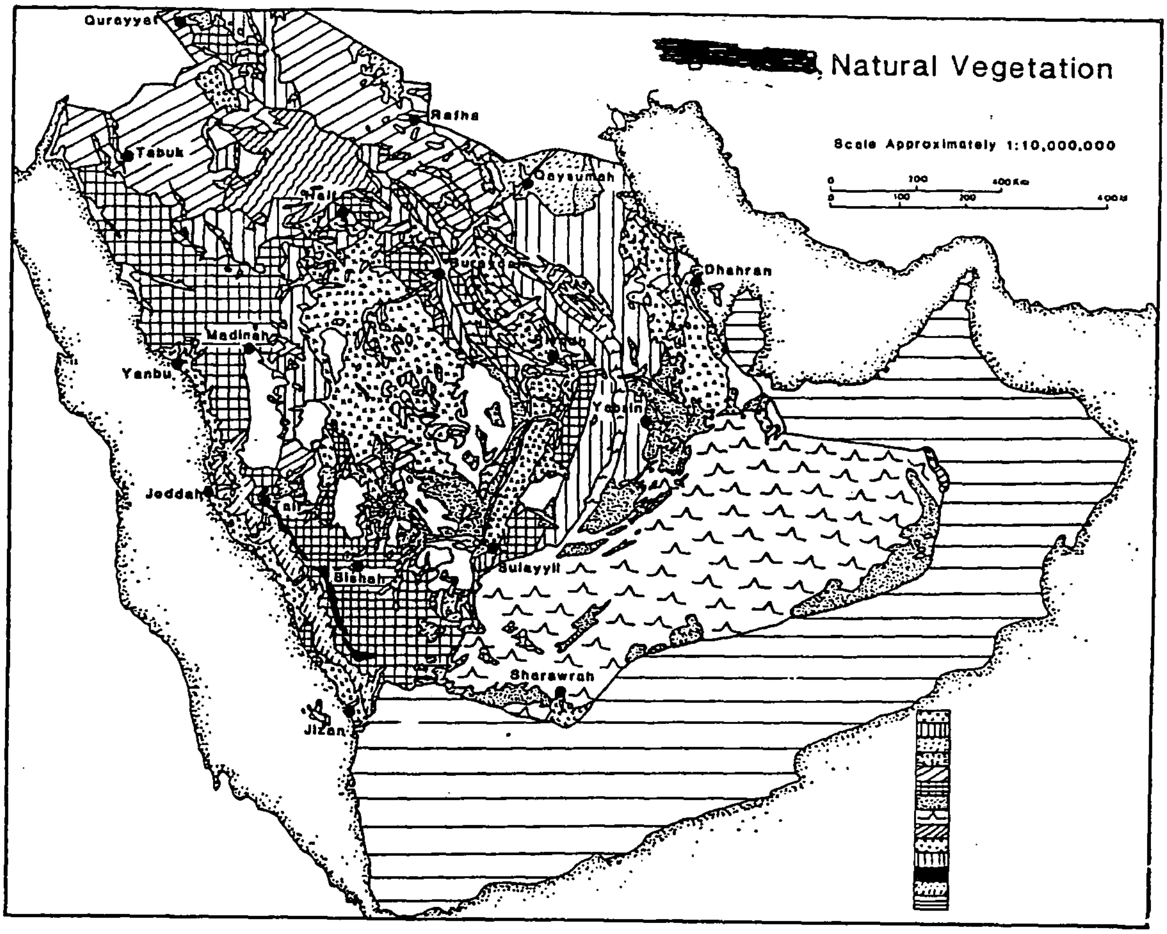
The balance between forms of vegetation and soils is delicate. The death of plants, or parts of plants, followed by the accumulation of organic matter in the soil, helps to maintain the life cycle. Deficiencies of certain soil elements may have a considerable effect on plant organs. The nature and condition of particular organs, the leaves perhaps, may indicate the presence or absence of specific minerals in the soil. Soils are zonal in that they are heavily affected by the climatic and vegetational conditions of the area in which they occur. They are also built of material transported from nearby regional soil types. Thus, the alluvial plain of the Red Sea coast is inhabited by almost the same plant communities, or with little modification, as the lower mountain zones. Despite the fact that alluvial soils in flood plains differ from one another in origin and profile development, most are intensively cultivated and they can be separated in terms of vegetation (MAW).

The natural vegetation in Saudi Arabia can be divided into fourteen predominating natural vegetation types. The distribution of these types are shown in Figure 2.16, to which the following list is the key.

1. *Panicum turgidum* - perennial grass.
2. *Rhanterium epapposum* - shrublet.
3. *Halsoxylon salicornicum* - shrub.
4. *Zilla spinosa/Haloxylon species* - shrubby plant/ shrub.
5. *Artemisiaherba - alba* - shrubby plant.
6. *Acacia plumosa* - annual or perennial grass.
7. *Aristida plumosa* - annual or perennial grass.
8. *Cyperus conglomeratus / Calligonum comosum* - sedge/shrub.
9. *Calligonum comosum* - shrub.
10. *Suaeds* species - herbs and shrubs.
11. *Aristids adscensionis* - annual grass.
12. *Juniperus procers* - conifer tree.
13. Barren of vegetation.
14. Data Not Available.

Various grasses, trees, bushes and weeds exist in the rangeland areas. The most prominent tree varieties are *Paspalidium diserterum* (Toman), *Panium turgudum* (Ush 6), *Acacia tortiles* (Somar), *Zygophylum spp.* (Al-Harm), *Halopeplis perfoliata* (AL Kurrayz), *Haloxylon salicornia* (Al Ramthm and *Acacia* (Salam), which grow on coastal sand dunes and the fringes of both coastal and inland sabkhas, where the salinity of the sandy soil is 23,000 ppm. Other halophytes, such as *Dipterigium glaucum*

Figure 2.16: Natural vegetation in Saudi Arabia



1. *Panicum turgidum* - perennial grass.
2. *Rhanterium epapposum* - shrublet.
3. *Halsoxylon salicornicum* - shrub.
4. *Zilla spinosa/Haloxylon species* - shrubby plant/ shrub.
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9. *Calligonum comosum* - shrub.
10. *Suaeda* species - herbs and shrubs.
11. *Aristida adscensionis* - annual grass.
12. *Juniperus procera* - conifer tree.
13. Barren of vegetation.
14. Data Not Available.

(Arfaj) and *Tribulus tongipetalus* (Zahr) grow on sandy soils near agricultural land where water is plentiful. In the mountains, range conditions are generally good to excellent. In fact, rainfall distribution allows a more regular growth of plans in the mountain area than on the other areas' plains. This being the case, the local flora consists of few species, and even these are limited in development due to the extreme lack of rain and high prevailing temperatures.

Perennial grass is found in central Saudi Arabia and in the western plain near Yanbu and on the eastern plain. Small shrubs are found near Ha'il and in Al-Nafud Desert and near Yabrin. Shrubs are also found near Qaysumah in the north. The shrubby plant/shrub is found in the north of Saudi Arabia. Artemisiaherba alba shrubby plant is found near Tabouk and near the Saudi-Iraq boundary in the north. Annual or perennial grass is found near Madinah and Bishah in the south and near Riyadh in the centre after rainfall. Aristida plumosa annual or perennial grass is found in south Rub-al-Khali and Nafud and near the mountains. Sedgel shrub is found in the Rub-al-Khali. The callisonum comosum shrub is found near Ha'il City in the north. *Suaeds* species herbs and shrubs are found near the west coastal plain and west plain. Annual grasses are found in the Nafud Desert and near Madinah City in the west. Conifer trees are found in the southern mountains. The areas near Sharawrah City, south west of Rub-al-Khali and north of Sulayyil City, and north east of Saudi Arabia are entirely devoid of vegetation (Al-SHarif, 1977).

In Saudi Arabia, there are 53 vegetative species of grass and 8 species of shrub of the decreaser type, and 7 species of grass and 25 species of shrub of the increaser type. There are 14 different species of invading perennials and of the prominent annuals, 8 grass species and ten forb species. Vegetation in Saudi Arabia can be classified by habitat into five categories in terms of density and quality: the wadi areas, deep and dune areas, mountain areas, the desert plain and limestone outcrop areas, as in Figure 2.16.

The wadis are the most favourable vegetative habitats with runoff water bringing silt and nutrients along with the additional moisture. The shrubs and grasses form more vegetative cover than on surrounding uplands. The principal vegetation type of areas of deep sand is a decreaser grass. Following the rains, vast green carpets of annual grasses and herbs cover the sands. The mountainous areas exhibit a forest flora. On the western slopes of mountains, natural forest stands occur from altitudes of 2,400 to 3,000 m and also from 2,000 to 2,400. The mountain flora is varied and rich as can be appreciated by the range of species reported in Figure 2.16.

Desert plains and outcrops of limestones have plants scattered in pockets only where soil has accumulated. Throughout areas of Saudi Arabia, a xerophitic steppe type of vegetation dominates. The tree formation in this area consists of dwarf species of Acacia. Toward the bottom of the wadis and along the main channels large trees of Acacia, temarix and zizyphus are in abundance. As one approaches the mountains, at an altitude of about 1800m, trees, bushes and thickets get taller and denser. Within the mountain range, the vegetational species appear to represent both the Mediterranean influence and the sub-tropical influence, such as the *Olea chrysophilla* and *Juniperus procers* which are often quoted as indicators of the ecological limits of an area. The vegetation distribution is strongly controlled by temperature and rainfall and there is a very close relationship between the climatic and vegetation patterns in the country (MAW).

Some of the most striking changes in cropping are made, however, by the degree to which farmers can control the amount and quality of water available to plants either by irrigation, drainage, or improvement of water quality. However, alongside extensive modifications to the soil-water relationship has developed a kind of dry farming in association with drought-resistant plant strains. The use of the cultivated soil as a moisture-storage reservoir during a fallow year conserves the variable yields of central Saudi Arabia. Aerophytic plants intercept air-borne moisture which might otherwise not be precipitated in the locality. Some tropical coastal vegetation survives largely on intercepted mist and cloud, in some cases they may even exceed their interception capacity and contribute to streamflow and ground water recharge.

The future of the vegetation cover is difficult to foretell with certainty if one is to judge by trends over the past two decades. Things would have been different had it not been for the availability of alternative materials which substituted for direct and indirect consumptive use of the natural vegetation (MAW). There is a relationship between the vegetation cover and the hydrology of the region, the quality of land on the one hand, and the general well-being of the community on the other. It is only logical that treatment of land degradation resulting from poor watershed management should start at the origin of the problem itself: at the upper reaches of the catchment area. The rugged terrain and the limited rainfall imposed serious constraints on such human occupation (Al-Sharif, 1977).

The concern here is with natural vegetation, i.e. vegetation which develops without appreciable interference and modification by man. The vegetation of the area has been thoroughly studied. The semi-arid vegetation of the area belongs to the Sudanian region in terms of phytogeography. It should be noted that this phytogeographical region deals principally with plant species and not with ecological relations. The hot deserts, such as Rub-al-Khali, are rarely completely without vegetation. Even the sand desert bears occasional tamarisks and tufts of coarse, spiky grass in the hamada such as Tihama. Elsewhere there are dwarf salt-bushes. Most vegetation exists in a virtually dormant state but after many years may burst into growth for a few days as the result of rare downpour. Exceptional rain cause the more continuous vegetation cover of the margins to advance temporarily into the true desert. Vegetation growing in wadi channels may be regarded as a kind of surface roughness which reduces the capacity of the channel and retards flow. In shallow streams, the growth of hydrophytes raises the surface-level either all the year round, or at least in the warm season, and in some large tropical wadis (rivers) a considerable retardation of flow and loss of discharge occurs directly due to vegetation (MAW).

2.7.2 Vegetation in Tihama Asir

Vegetation in Tihama Asir is predominantly determined by its climate, and in particular the two main monsoonal and Mediterranean climatic influences which overlap in this region. Floristic elements of the southern part of Asir mountains may also be found in Hijaz mountains, one thousand kilometres to the north. The coastal plains has Panicum-turgidum grass, areas of high plateau are very sparsely covered by drought-resistant desert varieties again as in the coastal plains. After the rains, however, the desert bursts into bloom with thousands of unexpected species. In addition, along the Wadi Jizan bed (Figures 2.17-2.18) one can observe a variety of trees and shrubs such as *Salvadore perscia* (Arak), *Spinachristic* (Nabak) and *Dom-plalm*.

The vegetational subdivision of the area is based upon a combination of the general distribution and the ecological distribution of plant species. It can be recognised that there are at least four types of vegetational features based on ecological settings in the area (MAW):

1. Juniperus woodland is confined largely to the watershed zone where humid conditions prevail, and the vegetation can thrive in alluvial soil after rainfall. However, this type of cover can occupy areas differing considerably in soil type and water.

Figure 2.17: *Natural vegetation with alluvial soil upper Wadi Jizan*

Figure 2.18: *Natural vegetation upper Wadi Jizan near the dam*

2. 'Rain' desert, in which vegetation is patchy and very sparse, but still maintained by limited rainfall (Figure 2.18), for instance, the vegetation found above Wadi Jizan Dam. When this is abandoned, serious soil erosion follows, endangering the whole ecological and hydrological cycle.

3. Run-off desert in which the amount of precipitation is insufficient to support any kind of vegetation except in depressions and lowlying places where ground-water or run-off moisture accumulates.

4. Absolute desert in which there is no sign of vegetation.

Woodland vegetation is replaced in part by evergreen plants, in places forming dense thickets, 2-3 metres high. The basic characteristic of almost every plant is that it has adapted in some way to the summer drought, for example small, hard, evergreen leaves, or increased activity during the summer rains. The expectation is for a well distributed rainfall of 150-300 mm with temperatures ranging from 10°C to 21°C. A dry season may be of brief duration. Such conditions are found in the Asir mountains and in other rangeland areas, including sabkhas and sand to sandy loams (Figure 2.19). This kind of vegetation requires soil moisture after rainfall, the most common plants are *Suada fruiticsa*.

The main plant in the desert is the Acacia which is bare for most of the year. An occasional tropical downpour produces a shortlived burst of plant growth. The plant blossoms exotically for a brief season surrounded by a carpet of grass which springs up, soon to be scorched by the heat (Figure 2.20). This area consists of many woody plants, among which *Lasiurus husutus*, *Indigofera spinosa*, and *Chechus cilious* are dominant. In other rangeland areas, including sabkhas (saline soils) and sand to sandy loams, the most common plants are *Suada fruiticsa*, *Lasiurus hirustus*, Acacia tortuis, and *Depterygium glaucum*. On the sand dunes, *Depterygium glaucum* is also found, as well as *Panicum turgidum* and *Leptodemia pyrotechnica*. Range conditions vary from

Figure 2.19:

NATURAL VEGETATION COVER WITH SIOL MOISTURE IN TIHAMA.

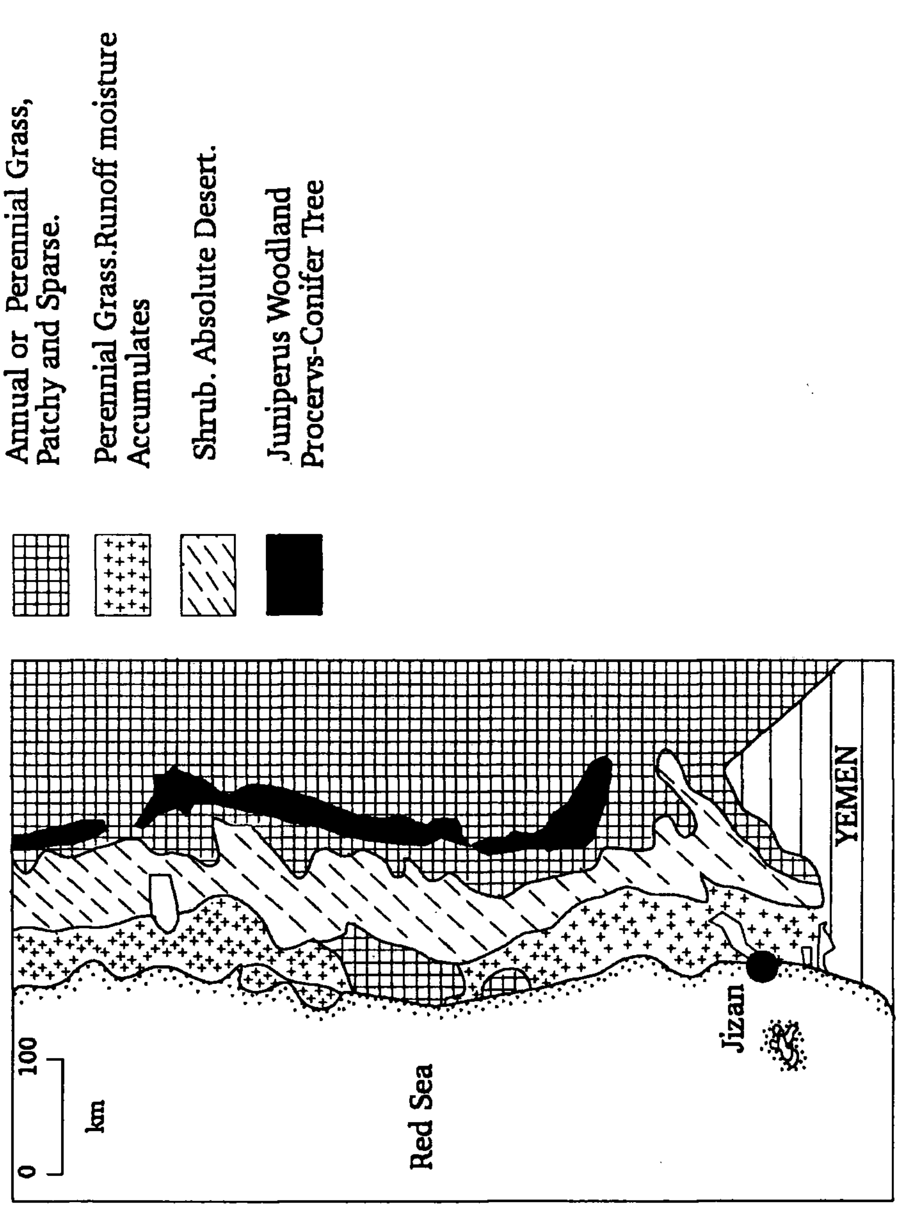


Figure 2.20: *Tihama Asir natural vegetation*

fair to good on the coastal plain to good on the wadi plains and in the wadi beds. In the mountains range conditions are generally good to excellent. In fact, rainfall distribution allows a more regular growth of plants in the mountain area than on the coastal plain. This being the case, the local flora consists of few species, and even these are limited in development due to the extreme lack of rain and the high prevailing temperature.

2.8 The Hydrological Cycle

The availability of water has always been a decisive factor in maintaining our lives. Man's earliest dwelling places were determined by the existence of rivers, lakes, wells and other places of sufficient fresh water.

The cyclic movement of water from the sea to the atmosphere and thence by precipitation to the ground, where it collects in streams and as groundwater and runs back to the sea, is referred to as the hydrological cycle. Water appears in liquid, solid and gaseous states. Emphasis is given here to the processes on, or within (such as interflow), the land surface with no detail of water-transport mechanisms operating within the atmosphere and sea. Although this concept of the hydrological cycle is over-simplified, it affords a means of illustrating the most important processes that the hydrologist must understand.

The concept of the hydrological cycle is a useful point from which to begin the study of hydrology. The driving force of the circulation is derived from the radiant energy received from the sun. The bulk of the Earth's water is stored on the surface in the oceans, and hence it is logical to consider the hydrological cycle as beginning with the direct effect of the sun's radiation on this largest reservoir. Figure 2.21 indicates the kinds of water on the planet. The bulk of the Earth's water is stored on the surface. Between 95% and 96.5% of the total water is saline. Ice represents between 1.7% and

Figure 2.21: The worldwide occurrence of water by type (percentage)

Saline Water [Inland Seas]
95%

Fresh Water [Inland areas]
5%

Surface
1%

Ice
4%

Ground Water 97%

Surface Water 2%

Atmospheric Humidity 0.95%

Vegetation 0.05%

Source : Reference Ministry of Agriculture and Water

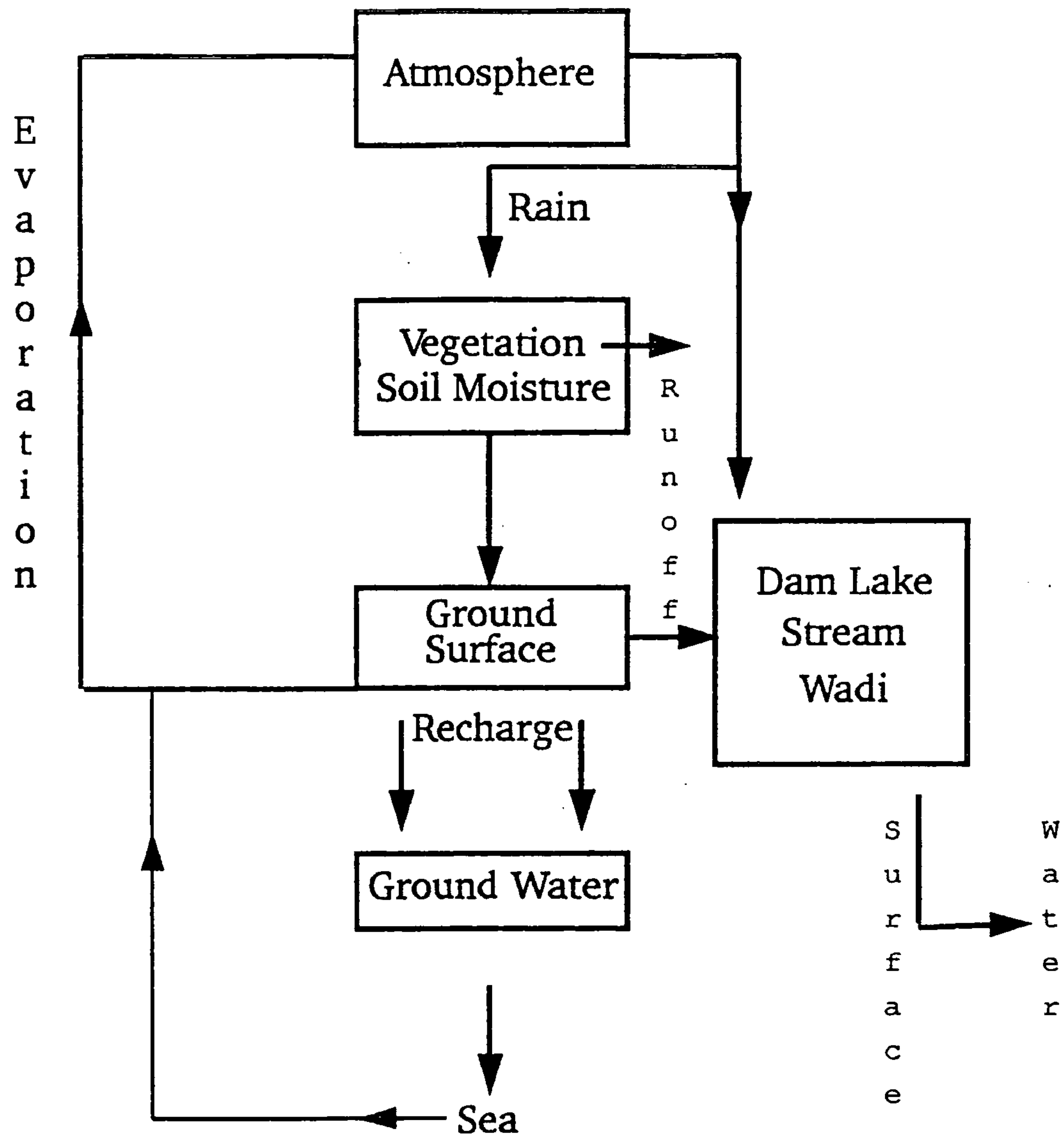
4% of the hydrological cycle and may be stored naturally. About 1.7% of water is groundwater. Estimates of the quantity of water stored in the atmospheric water system, the driving force of surface water hydrology, vary between 12,900 km^3 of water, or less than 0.01% of all the earth's water, to 0.1%, still a very small proportion (Chorley - translated by Al-Khashab, 1979).

Of the water supply, about 1% actually passes through the hydrological cycle. Rainfall reaching the ground may collect to form runoff. Of total water storage in the earth, run-off forms about 2%, groundwater 97%, humidity 0.0095% and vegetation 0.05%.

Were the Earth a uniform sphere, the quantity of water would be sufficient to cover the planet to a depth of 2.6 km (1.6 miles).

This cycle (Figure 2.22) is visualised as beginning with the evaporation of water from the oceans (seas). The resulting vapour is transported by moving air masses. Under appropriate conditions, the vapour condenses to form clouds, which in turn may result in precipitation. The precipitation which falls on land (as distinct from that which falls into the sea) is dispersed in several ways. The greater part is temporarily retained in the soil near where it falls and is ultimately returned to the atmosphere by evaporation and transpiration by plants (Abdulaziz, 1984). A portion of the water finds its way over and through the surface soil to stream channels. Some water penetrates further into the ground to become part of the groundwater. Under the influence of gravity, both surface stream flow and groundwater move toward lower elevations and may eventually discharge into the oceans (seas). The hydrological cycle is a convenient means for delineating the scope of hydrology as that portion between precipitation on the land and the return of this water to the atmosphere or ocean. The cycle also emphasises the four phases of interest to the hydrologist: precipitation, evaporation and transpiration, surface stream flow, and groundwater (Chorley - Al-Khashab, 1979).

Figure 2.22: The hydrological cycle of Saudi Arabia



Source : AbdulAziz M. H. and Ministry of Agriculture and Water.

The land phases of the hydrological cycle have an enhanced importance in nature since evaporation is a purifying process; the sea's saline water is transformed into fresh precipitation water and therefore water sources and natural reservoirs on the continents consist largely of fresh water. The exceptions include groundwater storages with dissolved salts (brackish water) and surface waters polluted by man or natural suspended solids. Most of the earth's water is stored in the ocean, all as salt water. Nearly all of the fresh water is frozen in the polar ice sheets. A measure of that locked up in polar ice can be grasped when it is considered that the Antarctic ice cap, if it melted uniformly, would yield enough fresh water to supply all the rivers. One could cite many other interesting facts about the water in storage and water in motion, but one fact stands out above all others; the continuous operation of the water cycle is absolutely essential for all life on the land.

In hydrological studies the primary focus of interest is the transfer of water between these stores (Figure 2.22). The exchanges of water involved in the various stages of the hydrological cycle are evaporation, moisture transport, condensation, precipitation, and runoff, as seen in Figure 2.22.

Water evaporates from the oceans and land surface to become part of the atmosphere. The water vapour is then transported and further elevated in the atmosphere until it condenses and precipitates on land or oceans. Precipitated water may be intercepted by vegetation, flow on the ground surface, infiltrate, flow through the soil as substrate flow or be discharged into streams as surface runoff. Much of the intercepted water and surface runoff returns to the atmosphere through evaporation. The infiltrating water may percolate deeper to recharge ground water, later emerging in springs or seeping into streams to form surface run-off, and flowing out to the sea or evaporating into the atmosphere as the hydrological cycle continues.

Water which has infiltrated the ground flows slowly through aquifers to river channels or sometimes directly to the sea. The water that infiltrates also feeds the surface plant life and gets drawn up into this vegetation where transpiration takes place from leafy plant surfaces (Chorley - Al-Kashab, 1979).

The water which remains on the surface in part evaporates back to vapour, but the bulk of it coalesces into streamlets and runs as surface runoff to the river channels.

When water reaches the earth's surface as rainfall, part of it evaporates directly from water surfaces or from the soil soon after it falls. Much of it follows one of several hydrological *pathways*, and may go through various processes before it returns to the atmosphere. Part of it is carried away as runoff by streams that ultimately lead to the sea or terminate in interior basins. Water held in the soil tends to percolate through the unsaturated layers to reach the water table where the ground becomes saturated, leading to aquifer recharge, or else the water is taken up by vegetation from which it may be transpired back into the atmosphere. The surface runoff and ground water flow join together in surface streams and wadis or rivers which may be held up temporarily in lakes but finally flow into the sea or ocean (Abdulaziz, 1984).

The Middle East's water supply is a product of precipitation on the mountains delivered from the south by the monsoonal air circulation system. The average annual rainfall, the only significant precipitation in these areas, has little practical meaning. As soon as the rivers reach the wide valleys, where the aridity becomes more intense, the flow velocity drops. Only a handful of rivers carry water as far as the sea, such as the Nile and the Euphrates.

The historic, direct relationship between man and water has not ended in modern times; the situation has become increasingly complex. Current water demands and anticipated future needs present considerable uncertainty. Population growth, urban and industrial expansion and demand for food are the main causes of this complexity.

There are regions where it is reasonably certain that the right amount of suitable quality water will be available at the right place at the right time. However, this is seldom the case within the wet areas of the world, and is becoming even less common as agricultural, industrial and domestic demand for water supply increase, and as deforestation, land development and possibly climatic fluctuations alter water supply availability.

2.9 Summary of key factors

Saudi Arabia occupies a vast area, and is characterised by immense variations in topography, climate, hydrology, soils and vegetation. The extent to which each of these has been studied and detailed locally is variable, and so data can be patchy.

Topographically, Saudi Arabia can be described as an peninsula plateau ringed in part by mountain ranges. This structure influences the precipitation over Saudi Arabia. Precipitation is mostly limited to a short winter season, although parts of Saudi Arabia experience rain maybe only once every ten years. As a result, much of Saudi Arabia is arid. The predictably high temperatures make for high rates of evaporation, and run-off from precipitation rarely lasts long, either percolating into the ground, or finding its way to the sea. Consequently, Saudi Arabia experiences problems over water resources, most of which are stored in various categories of drift and bedrock aquifer. Whilst there is a considerable variety of vegetation, this is often sparse, not simply because of the lack of water, but also because the predominant soil types are far from rich in humus and nutrients. The country is attempting to develop industrially, and this makes considerable demands on the supply of water.

Turning to Tihama Asir, there are aspects of this region which represent a microcosm of the entire country. However, topographically it has a coastal plain, an area of foothills, and a mountainous region. This is in a sense the reverse of Saudi Arabia as a whole. The reversal is reflected in the hydrology of the region: measurable precipitation in the mountains peaking twice a year. The temperature is, predictably, very hot, particularly on the coast, and evaporation rates are correspondingly high, exacerbated by the local winds. The vegetation is similar to that of elsewhere in Saudi Arabia. The soil of Tihama Asir is largely concentrated in limited areas mostly distinguished by access to ground water. The historical prevalence of such small, scattered settlements makes it evident that shortage of water was the greatest obstacle facing the life of the region.

Chapter Three

Surface Water

Introduction

In this chapter, surface water in Saudi Arabia is examined, along with the relationship between rainfall and runoff. Wadis are studied, looking at runoff infiltration into the sub-surface, groundwater, basal flow and springs. Wadi basins are examined, relating them to a distinctive region, according to elevation, rainfall and runoff. The study of the monthly and annual surface flow of wadis is useful for planning the development use for domestic and agricultural irrigation.

The runoff and volumes are discussed for years of exceptional, medium and least rainfall to illustrate the point that the median of the runoff volumes for the period of flood records can be accepted as the reasonable annual recharge to the groundwater, and study of the runoff from individual storms would be useful for flood control planning, the comparatively large amount of surface water of a particular rainy year, 775mcm (Table 3.1) is set against that obtained during years of very small flow, 24.58m^3/sec, can the actual mean contribution to groundwater recharge from surface water be identified. The catchment and runoff are discussed, together with the existing situation of the country that were once substantial contributors to irrigation water, but have recently dwindled in output with the receding water-table.

The development of springs as a source of water for irrigation and domestic use is examined.

3.1 Run-off

The movement of groundwater in the vast plains and sandy desert is extremely slow and the contribution to this inflow from a particular rainy year may not reach a point some kilometres away from the recharge area at the foothills for several years. the actual expected contribution to groundwater recharge from surface flow is derived for all the catchments within the country.

Despite the apparently low totals of rainfall over the country, flood runoff has been found to be a significant factor in the hydrological balance particularly in its role of subsequently infiltrating into wadi gravels and providing the major source of recharge. This may be attributed to the frequency of reasonably high intensity rainfall in the hill areas during the period, the relatively steep slopes and generally impervious nature of the underlying geology.

From observations of both rainfall and runoff it is apparent that the runoff occurs at different periods of the year over the eastern and western areas. In an area such as the At-Taif area, there is a tendency for more frequent runoff events during the spring, late summer and winter, whereas in the western areas, particularly the Wadi Khulays catchment, the main flood season occurs during October-November. In relation to the frequency of rainfall amounts and intensities to runoff events, an apparent paradox has been found to exist in those catchment areas in the vicinity of Taif. However, the lower amounts of rainfall in the spring and early summer produce an entirely disproportionate number of flood events when compared to the rainfall of the autumn which is more widespread, and of a greater amount. The tentative explanation of this paradox appears to lie in the hydraulic properties of the wadi gravels that make up the greater part of the wadi bed. Considering a cycle commencing in the autumn, all rainfall is slightly but significantly lower in intensity and there is little direct runoff, most of the surplus infiltration in the wadi gravels and shallow aquifers. From mid-November to the end of January this is released to base flow, gradually depleting through February and March. With the onset of the spring rains the wadi gravels, being at near full capacity and hence offering little capacity for infiltration result in more frequent flood runoff events. This gravel storage is then gradually depleted throughout the summer and the flood runoff that occurs in August is of sufficiently high intensity to overcome antecedent continues until further replenishment from the autumn rains occur. It is clear that rainfall/runoff relationships in the country are complex and it will therefore be necessary to consider these on a seasonal rather than an annual basis, and to closely integrate the results with shallow groundwater. This matter is being investigated further.

During the period March 1990-February 1991 it is tentatively estimated that there was a total rainfall input at some 1.418mcm over the country but it is not yet possible to assign a generalised estimate of what proportion of this occurred as runoff. This is because estimates of runoff from individual catchments for which runoff have been obtained show very wide differences. For instance runoff, expressed as a percentage of total rainfall for the period, is provisionally estimated to range from 0.15 to 1.65% in the eastern catchments, whereas runoff in the western catchments show a much higher range of values from 7 to 11%.

The wide difference in runoff expressed as a percentage of rainfall between the eastern and western catchments is tentatively ascribed to differences in topography, season, the concentration of rainfall into one short season in the west and dispersed over a longer period in the east, and to differences in agricultural practices between these two areas.

The percentage of the catchment areas terraced is not generally proportional to the reduction in runoff for soil and water conservation work are of two types. The first time comprises the contour terracing of hill slopes in the higher rainfall areas. All these terraces are effective in preventing runoff from reaching the drainage channels except on those rare occasions when intensity and duration of rainfall exceed the infiltration rate and storage capacity of the terraced soil. The second type comprises valley bottom terracing which depends partly on direct rainfall, partly on some degree of lateral runoff from adjacent hill slopes and partly on diversion of flood flow by somewhat simple earth embankments.

To summarise, the following tentative conclusions have been reached with regard to runoff but it is stressed, once again, that the short period being considered provides no indication of long term conditions and at their best they provide only provisional guidelines for possible development:

(1) It is apparent that runoff occurs at different times of the year for different areas, this being directly related to the seasonal and type distribution of rainfall in both space and time.

(2) The infiltration capacity of the wadi gravels has an important bearing on seasonal rainfall/runoff rates and present indications are that this may follow an annual pattern of dialogue and recharge.

Surface water flow is characterised by:

(1) the rarity of permanent flow;

(2) the violence and brevity of floods.

All the wadis only flow intermittently due to heavy rainfall, when the violence of the floods makes the estimation of flow very difficult. The catchment of a wadi is considered at a certain point of its course is the area limited by the contour inside which the precipitated water moves towards that points of the wadi. In practice, it will be admitted that the catchment area usually coincides with the topographical basin, the limit of the latter being the ridge separating it from the next basin.

Run-off may be subdivided into several components: direct precipitation into stream channels and swamps; surface run-off comprises water that finds its way over the ground either as a sheet flow or in trickles and streams to main stream courses. The term overland flow is sometimes used as an alternative to surface run-off, but is better applied to sheet flow of water from the point at which precipitation reaches the ground to the point at which it enters a defined channel. Recharge moves to groundwater more slowly than surface run-off and is likely to be greatest when thin, permeable soil overlies impermeable rock or hard pan layers. Where such conditions exist, interflow can be an important component of the total run-off. Groundwater flow is the contribution to run-off made by groundwater when it reaches streams channels. High intensity storms which result in run-off have been observed over most parts of the project area, but measurement of such infrequent occurrences are not yet adequate to provide reliable estimates of duration, frequency, amount and distribution of this surface water.

Even minimal runoff storms in Saudi Arabia total 2810 mcm/y (MAW). Flows may be stored, diverted or recharged, but the very magnitude of Saudi Arabia's land mass rules out significant applications except perhaps in urban settings. In Tihama Asir, runoff totals about 2448 mcm/y (MAW). This chapter examines the relationship between rainfall and runoff within a wadi basin, and also the attempts to control flooding and store water in wadi channels between levees. The hydrology of the main wadis in Saudi Arabia is studied, and dam types in Saudi Arabia are described. Pollution is an important issue in this chapter as it accompanies runoff.

Surface runoff occurs because water is unable to infiltrate, that is to pass through that surface of the soil quickly enough. First the water wets the soil grains by forming hydrogen bonds with the mineral surfaces. Then, as more water enters the soil, surface tension forces cause water to enter most of the small pores, with numerous menisci forming at the interfaces between air and water. As more water seeps into the soil, it destroys the menisci and the force of gravity takes over and moves the water down toward the water table (Noury, 1984; MAW, 1989).

Direct runoff occurs annually in Tihama, but irregularly in other parts of the country. The wadi basins of the Tihama area can be divided into distinctive regions according to elevation and agriculture irrigation. This is due to the variability of flood intensity, duration and time of occurrence and also due to traditional water rights. By use of dams, such as that on Wadi Jizan, there is a system of flood control, as well as irrigation to improve water supply to the fields. The purpose of the flood control is to regulate floodwater flow in the wadis, to protect the lands downstream from damage during the flood flows, and to enable the release of stored water for controlled spate irrigation.

3.1.1 Relationship Between Rainfall and Run-off

Run-off is that part of rainfall which appears as surface flow in wadis or overland sheet flow and is measured in two ways:

(1) as the rate of flow that passes a particular point in a given period of time, expressed in cubic metres/second; and

(2) as the annual total volume which is expressed in millions of cubic metres (mcm).

The number of rainy days for each month were counted as the days having any amount of rainfall. The monthly averages for the calculated is based on the available data for any particular month. The total monthly rainfall values and the number of rainy days, according to the availability of monthly data. The daily average rainfall values for the selected stations and the daily inflow into wadis were plotted for each of the particular months. Generally, the peaks of rainfall and runoff occur on the same day especially for values of the average daily rainfall of the area. The coincidence of the daily peaks of runoff and average rainfall on the same day indicates that the time-lag between rainstorm occurrence on the catchment area and the arrival of the corresponding surface runoff at the catchment is within 24 hours. Nevertheless, the type of the daily and monthly rainfall-runoff relationship which came to be of the same nature would lead to the fact that the annual rainfall-runoff relationship would not be different and it is anticipated that the total annual runoff into the area are proportionate to the square of the total rainfall over the catchment area.

The limiting resource in the development of Tihama Asir is water in the form of direct rainfall, surface run-off and ground water. Surface run-off from time to time flows through wadi channels in the area and recharges the ground water.

The climate of the different hydrographs is not uniform, as the period of recording varies from 2 to 21 years. For some purposes, an estimate of total runoff volume from a basin within a given time period is adequate. More often, however, an estimate of the instantaneous peak-flow rate is required for design, and in many cases the complete hydrograph is needed. Hydrological methods must therefore include techniques for converting estimates of runoff volume to estimates of flow rate. No wadi has perennial flow in the Asir and some regionalisation as found for rainfall is also evident. A long term correlation between rainfall and run-off discharge is also readily seen, though it has to be quantified. Large variability from the long term mean seems to be the rule rather than the exception. The total mean annual run-off for all the stations amounts to 950 mcm, which is nearly 5% of the mean rainfall over the Asir area. The widespread use of rain enhancement technology is estimated to produce as much as between 4% and 40% increase in surface run-off. The impact of precipitation management on run-off will thus vary to a large extent and will depend on factors as:

(a) character of the watershed; and

(b) duration and intensity of precipitation.

Thus in dry watersheds as is typical of Asir, additional precipitation will result in run-off only when the demands for evaporation and infiltration are satisfied. The infiltration rate depends on the water viscosity and the soil permeability. As the viscosity increases, the water flows more slowly, so less will infiltrate from a cold than from a warm rain. Permeability is a property of porous materials that determines the rate at which fluid flows through the material. Water flows more readily through sand than through clay, therefore, sand is more permeable than clay. Anything that restricts flow reduces permeability, hence lowering the infiltration rate.

3.1.2 Surface water in Saudi Arabia

A flood in a large wadi occasionally occurs in KSA but is usually localised. After the surface flow has travelled a few kilometres, it generally disappears into the dry wadi bed. Therefore, in addition to the effect on them of the low rainfall, large amounts of run-off including flood flows, infiltrate into the wadi alluvium. Run-off may not occur at all in some wadi basins during some years because the rainfall there may be insufficient to generate run- off.

Run-off in KSA is generally irregular and relatively small owing to the small amount of rainfall. Because rainfall is scant, perennial streams are non- existent. However, in the upper reaches of the wadis draining the Red Sea escarpment the base flow may last for several months and the wadis may thus tend to have perennial characteristics. Despite a small amount of rainfall in most parts of KSA, run-off does not occur especially where there are mobile sand dunes such as the Great Nafud and Rub-al-Khali deserts.

Although runoff in Saudi Arabia is generally influenced by the size of the catchment (MAW; Noury, 1984), its shape and the amount of rainfall, it is also affected by the localised incidence of rainstorms. Whether most of the rain is caused by air flow from the west and north west (Mediterranean) striking the catchment to the west of the watershed, or from the southwest (Monsoon) striking the catchments to the east of the watershed, the slope aspect, in most of the catchment or of individual wadi sites or their tributaries, is more important than the general rain-causing conditions.

Catchment size is an important factor in the volume of runoff, when the rainfall is widespread would naturally have a greater runoff volume than that of the adjacent, smaller, the period mean runoff of the former being nearly double that of the latter. The localised rainfall incidence in southern Saudi Arabia, give rise to larger runoff volumes in the smaller catchment of the north. That the larger runoff is found in the southwest of Saudi Arabia, west of Asir Mountain, about 60% from the runoff. The time of runoff in the Red Sea area of a flow is about 39.8 m^3/sec, and about 27m^3/sec south of Jeddah, and about 8.2m^3/sec north of Jeddah (Noury, 1986).

The runoff coefficient is highest in southwest Saudi Arabia where it ranges from 40% to 60%, and is lowest in the north of Saudi Arabia, where is ranges from 5% to 20% (Noury, 1986). The runoff ratio appears to be closely related to the amount of basin rainfall and the resulting runoff volume; the higher the runoff volume, the higher is the runoff coefficient.

The runoff coefficient is higher for wadis in the western slope of the mountain block than for those in the northern, and eastern limestone mountain block. Higher values are also measured for the west flowing than for the east flowing wadis. Runoff coefficients are even lower in wadis of the Piedmont plains as they debauch onto the gravels and sands of the plains, with their high absorption capacity and broader flow channels, such as Wadi Yadamah in Najran area, where the annual runoff rarely exceeds 16%, even in years of high rainfall/runoff. The general runoff ratios are 12% for wadis in the limestone and 16% for wadis in the ophiolite catchments (MAW).

With regard to the surface run-off, the escarpment line presents an obvious dividing line. The volume and velocity of the run-off is dependent on the intensity and duration of the rainfall and on the size of catchment that it covers. High intensity rain storms generate considerable run-off, whilst low intensity rainfall may reach two or three times the amount without generating much run-off. Although there is an association between the high monthly rainfall values and run-off, it is the single rainstorm which is more important in determining the run-off. The run-off which occurs as wadi flow infiltrates the alluvial deposits within the wadi where it generates sub-surface groundwater. However, some of the runoff is also lost due to evapotranspiration. Floods on large flows occur occasionally, but are usually local. Surface flow tends to run only a few kilometres before disappearing into the dry wadi beds. The effect on the wadis of lower rainfall is also ephemeral because of the large amounts of runoff that infiltrate into the wadi alluvium. A thunder storm that produces run-off can occur at any time in any wadi depending on climatic conditions and physiographic characteristics of the drainage area. Therefore run-off varies, considerably from place to place, season to season, and year to year. Although run-off varies, certain patterns generally occur which closely follow the patterns of average annual rainfall. The mean annual rate of run-off in the Red Sea coastal area has been estimated as 39.8 cm/s. About 27 cm/s of this run-off occurs in south Tihama and 8.2 cm/s in north Tihama [Source: MAW].

The interflow and base flow components which constitute a constant flow, are not present throughout the entire year. This is due to a high soil moisture deficit which is caused by the high evaporation and small amount of rainfall. Thus, when a flood occurs, the depth of the underground water in the alluvium channel is far below the bed surface of the channel. Instead of water seeping to the stream during a flood, infiltration will take place. The only exceptional case is the seepage flow originating from the impound dam in Jizan to the downwards section of the stream, which is totally dependent on the flood reserves. Thus, the stream flow of the wadi is composed primarily of the overland flow contributed by the seasonal rainfall in the floods. Water in KSA comprises surface water, which includes run-off, lakes and reservoirs; and ground water, which includes soil water. The sources are not always separate. The amount of water available from the flow supply that lies beneath the Saudi Arabian surface is many times greater than that which flows or lies on the surface (MAW, 1989).

Records of runoff are collected in several wadis at 58 active runoffs. Most of these records are relatively young, but are sufficient to define a few general runoff characteristics in many wadis and also in some areas. For example, the greatest runoff in the country generally occurs during the period from March through April except in the southern Red Sea area where average monthly runoff is fairly uniform. Records of runoff in this area indicate that a relatively high average runoff may occur during any month of the year, and is somewhere between $27m^3$/sec to $39.8m^3$/sec (MAW).

The wideness of the alluvial embayments on the east coast more often allow spate flows to reach the sea even in years of moderate rainfall. To the west of the mountain divide owing to the greater distance between the foothills and the coastline and the high infiltration capacity of the western Piedmont alluvial plains, only occasionally do large flood flows, during years of high rainfall and low runoff, reach the sea through Wadi Yiba.

In cases during years of low to moderate rainfall, flood runoff ends up in the desert depression for hours or days, before drying up leaving an behind extensive area of fine silt. Rarely does overland flow reach beyond the central and south limits of the eastern Piedmont plains, but occasional ponding may take place if some degree of saturation of the alluvium of the plains has been effected by intermittent or continuous periods of rain shortly before a main storm. However, despite the fact that such ponded surface water bodies are exposed to high evaporation, some of this water infiltrates into the chloride- and sulphate-rich silts, gypsum and anhydrite-halite inland sabkha beds, becoming a contaminated brackish to saline groundwater surface.

In order for the flood runoff to reach the sea in a number of wadis on the west coast as well as Wadi Yiba to the west of the mountain divide, the alluvium in wadi courses must first reach a degree of saturation, a process less effective by short-lived thundery downpours, than by widespread, consistent rainfall over a long period, in the form of light to medium raindrops. The perfect condition for violent overflow to reach longer distances from the mountains, occurs when there is a heavy rainstorm after this initial saturation of the wadi alluvium.

The rare but typically intense precipitation in the southwest, northwest and central regions of KSA generates sporadic run-off. Such water is used for direct irrigation or for storage in surface reservoirs for later use. It may be noted that the Fourth Development Plan (1985-1990) estimates this resource as 900 mcm/y. Without further breakdown or location, a value of 700 mcm/y is used in this study in light of work done recently at MAW. Run-off may not occur at all in some wadi basins because the rainfall there may be insufficient to generate run-off.

3.1.3 Surface Water in Tihama Asir

The greatest amount of run off in Saudi Arabia is concentrated in the southwestern part of the country which consists of the western coastal area associated with the Red Sea escarpment (Tihama). The land between the Red Sea and the escarpment (Tihama) constitutes less than 10% of Saudi Arabia. However, 60% of the total runoff of the country occurs there. Furthermore, nearly 40% of this runoff occurs in the

Tihama Asir, although the Tihama Asir coastal area constitutes only about 2% of the land area of Saudi Arabia (Noury, 1983, pp.289-292).

In the Asir mountains direct run-off occurs annually whereas it occurs only irregularly in other parts of KSA. Torrential floods occur only after heavy rainstorms. Rainfall in the mountains of the Tihama region normally exceeds 300 mm/annum. The comparatively high rainfall, with relatively impervious geological formations and steep gradients provide for considerable direct surface water. Some streams occur in the mountains, and floods reaching the Tihama region of the plateau can be of major proportions and more frequent than others in KSA.

In the mountains, wadi flow is at the bottom of a deep gorge. On the plain, wadis are enclosed by flat banks only a few metres high. Obstructed by sand banks, the beds of wadis on the plain can be very wide: the largest of them is Wadi Baysh which is over one kilometre wide.

In order to study run-off in Tihama Asir, some well-observed floods were selected. All the run-off coefficient values were between two limiting curves, and there appears to be a system allowing the characteristics of a particular shower to be linked to those of particular run-off. It should be said that these floods occurred at different times throughout the year.

The area and the intensity of the storm and its distance from the gauging station are not the only factors influencing the value of the run-off coefficient for a given basin. Among other factors is the influence of the crops which take considerable amount of water from the wadis. One hectare of irrigated land absorbs an average of 5,000 m^3 of water per annum under present agricultural practices. In certain cases, as with Wadi Damad for example, the crops may absorb more than 40% of the mean annual flow.

The annual discharge of the wadis reached or exceeded one year in two are as follows:

Wadi Bayish	235 mcm/year
Wadi Sabya	30 mcm/year
Other tributaries of Wadi Bayish and Sabya	0.066 mcm/year
Wadi Damad	0.037 mcm/year
Wadi Jizan	0.090 mcm/year

The table above shows the annual average water discharge of the wadis in Tihama Asir: Wadi Bayish, 235 mcm; Wadi Sabya, 30 mcm; Wadi Damad, 0.037 mcm; and Wadi Jizan, 0.090 mcm.

With the exception of some pumped bore holes in Wadi Jizan used to irrigate gardens, all the water points are used for domestic needs.

Figure 3.1 shows the different basins in Asir. The climate of the different hydrographs is not uniform. The period of records varies from 2 years to 21 years. No wadi has perennial flow in the area and the same regionalisation as found for rainfall is also evident. A long term correlation between rainfall and runoff discharge is also readily seen. Bars in the hydrographs were drawn for mean monthly runoff for the year 1988 in order to contrast it with the climatological mean for the period under each hydrograph. The total mean yearly run-off for all the stations amounts to nearly one billion cubic metres (950 mcm)/year amounting to nearly 5% of the mean rainfall in the area. In Tihama Asir, the basins have a total mean yearly run-off of more than 600 mcm amounting to nearly 3% of the mean rainfall. All the basins of Tihama Asir flow to the Red Sea, such as Wadis Hali, Doqah, Bayish and Damad.

Under conditions of reasonably high rainfall, run-off over the Tihama Asir area plays a significant role in the hydrological balance, particularly in its role as the principal source of recharge to the alluvial filled wadis (Fig 3.1). This means the annual runoff for gauged wadis were related to the respective catchment area and found out that annual runoff in mm was 46.1, 34.1, 37.1 and 11.2 respectively. The source of the wadis

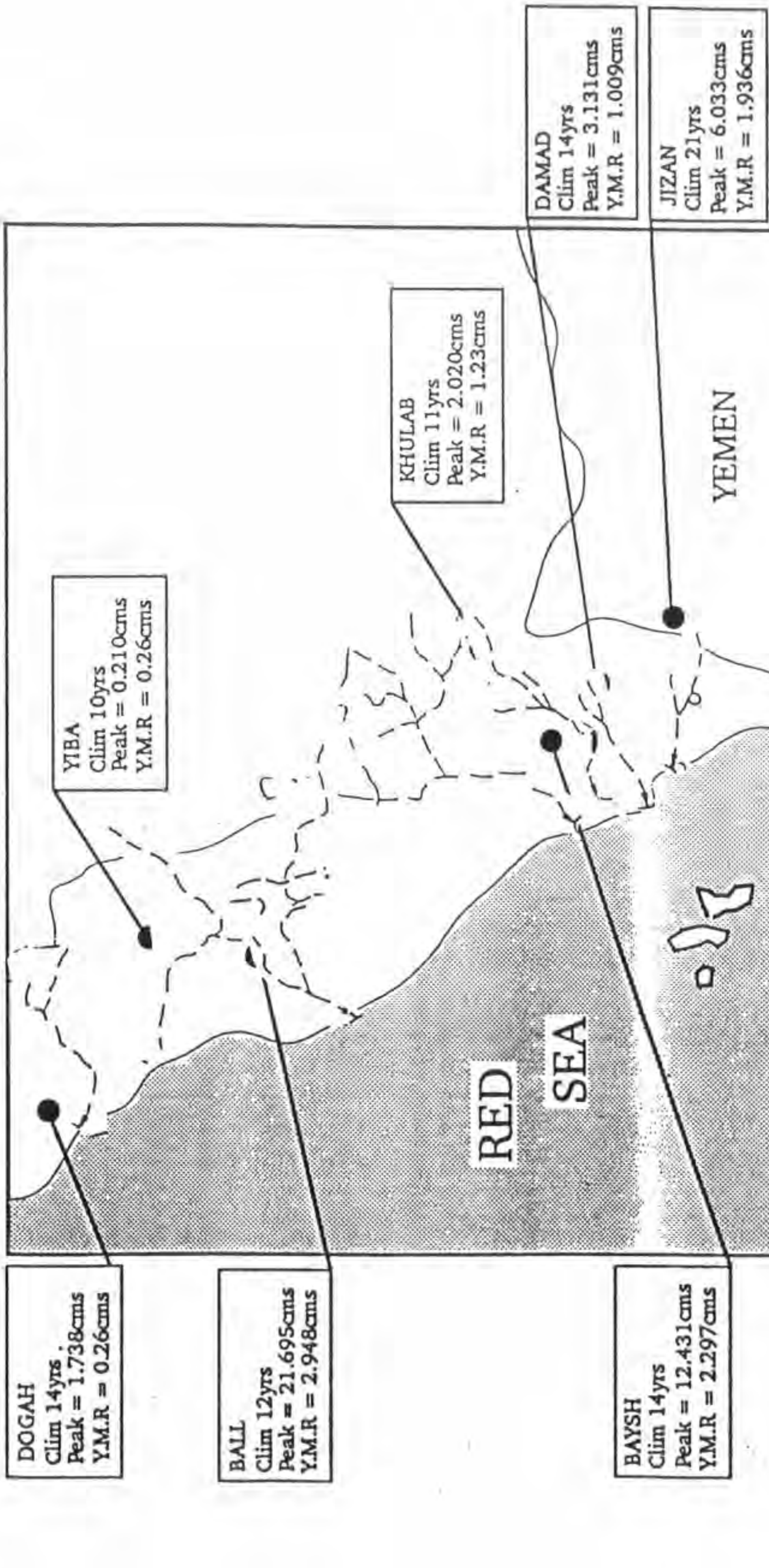


Fig.3.1 Yearly Mean Runoff in Tiham Asir Basins

are in the mountains of Asir eastern area which rises to heights of more than 3000m, which has heavy rain flowing westwards through the wadis. Downstream of the confluence of Jizan Wadi, the dam has been constructed.

The inflow over a period of more than 10 years is calculated for each month as well as for the annual values. The inflow occurred over the same period for each month and for the annual values were found.

About 53% of the mean annual inflow occurs during two months and they are in general by far the wettest months of the year with almost equal inflow for each of the two months (MAW).

Though precipitation is the only source of run-off in the wadis, the basin area, including the shape, size and drainage network of the catchment defines the dimension and magnitude of the flood. Infiltration is an important factor since the ground water level always lies beneath the top surface of the channel. However, the most influential factor is probably the shape, size and slope of the catchment area.

An elevation of the water head of the tributaries of more than 2300 m above sea level slopes down to an elevation of between 300 and 150 m near their mouths in the main wadis. The proportional loss of water by infiltration is consequently small. The velocity of water is high.

During 1974, extraordinarily intense floods occurred and these circumstances enabled observations to be made over a longer period of time. Recharge to groundwater takes place either directly from rainfall or indirectly from flood run-off. The latter accounts for the greater percentage of total recharge. Direct recharge from rainfall over Tihama Asir is confined to suitable topography underlain by weathered areas.

The overall analysis of the floods observed in the various basins of the study area in the light of the rainfall and run-off has been calculated. Annual surface water run-off for all the wadis of the study area was 1,440 mcm (MAW).

Rain which falls in storms, may produce floods which are sudden and short, and confining the run-off within limits. In Tihama Asir, run-off reaches the sea in an average flood. The intensity of rainfall from a single storm occurs in a narrow belt unless successive thunder showers fall within a short period.

The relationship between the wadi slope on one hand, and intensity, duration and movement of the rainstorm on the other hand is very important in terms of the flood peak. Taking the upper catchment, for instance, which was observed at Bayish, there are more than three tributaries flowing from east to west. Floods from Sabya and Damad join the main stream at roughly the same time, due to the track of the storms, which usually hit the catchment from east to southwest. When a rain run occurs in the catchment during a previous stream flow, the peak following the rainfall occurs rapidly and intensely.

The study of the possibilities of flood spreading covers about 7 wadis of varying importance, both in their strictly hydrological and topographical characteristics, and also in the characteristics of the land which they are capable of irrigating is examined in the conclusion to this chapter.

In normal years three wadis (Bayish, Yiba and Hali) have an annual run-off greater than 100 mcm, and several wadis (Khulab, Itwad, Qununah, Ahsihah and Alith) have an annual run-off between 50 and 100 mcm. Peak floods have been estimated around 10,000 m^3/s for Wadi Bayish and Wadi Hali, and in the other wadis between 4,000 to 5,000 m^3/s (MAW).

Run-off and surface water never stays long on the land surface, partly evaporating as a result of high temperatures. The degree of evaporation varies from one area to another but generally evaporation is high and constitutes a major water loss. Evaporative loss in the Tihama area has been estimated at 6-9 mm/day, and the potential evapotranspiration in the 1,500-3,000 mm range. Another part of the surface water infiltrates down to add to the underground reserve.

3.2 Springs in Saudi Arabia

The springs emerge from the edge of erosion remnants of a striking rock vein with acid volcanic rocks and a pegmatite vein, which approaches the recent wadi channel. The main terrace on the left side of the wadi is an erosion surface in the outcropping solid rock and on the right side of the wadi, the accumulated sediments are coarse gravels. The plantation of the main terrace is nearly 13m higher than the present wadi bed. The young terrace body lies below the main terrace and is about 5m high, it is made up mainly of losslike, silty, fine sands.

The water flowing from these has an average temperature above 10°C and often comes from springs that overlie portions of the earth's crust that contain magma chambers close to the surface. Springs may occur at the heads of wadis where they result from the convergence.

The movement of water on and through the surface of the stream has important consequences for the erosion, transportation, and deposition of surfacial materials.

The most common type of springs in Saudi Arabia are the contact spring, also called gravity, hillside, barrier, or outcrop springs. The springs issue from natural openings at contact of two formations. The water flows at the land surface from permeable strata that overlie less permeable or impermeable strata, which prevent or retard the downward percolation of the water.

Springs, which are hydrologically natural discharges of groundwater, have been an important source of water in KSA since prehistoric times. Several different types of spring are found in the KSA. Their occurrence depends on the permeability of the rocks, the topography and the level of water-table at given locations.

Hot springs containing large quantities of minerals dissolved from the surrounding rocks are sometimes called mineral springs, and the mineral water may be used for medicinal purposes.

Significant springs are found in the alluvium in Wadi Fatimah and Wadi Naaman in Makkah, and in the basalt near Madinah and Ula. In Central KSA in Kharg, springs issue from limestone formation and alluvial deposits and in the Quwayiyah in Qasim and Aflaj in Wadi Al-Dawasir, they issue from the Khuff formation. In many areas, springs are the most important domestic source of water and in some wadis they have been utilised to provide limited irrigation. Most flows are relatively minor ranging from 0.001 to as much as 0.3 m^3/s, but they can increase seasonally depending on the amount of rainfall (El-Khatib, 1980).

Thermal springs occur in Western KSA in Al-Lith south of Jeddah and Jizan in the coastal plain. The water in the reservoir rocks in such areas is so hot that the spring it supplies yield steam. The high temperature ground water in these types of springs, which can be either fresh or mineralised, is generally localised or occupies only part of the ground water reservoir. In Al-Lith and Jizan heated ground water emerges through large structural faults and mixes with cooler ground water during its rise to the surface causing dilution and reduction in temperature.

3.3 Springs in Tihama Asir

Al-Lith springs are on the left bank of Wadi Al-Lith about 20 km upstream from Ghumaiquah. They emerge from a small (20,000 m) extensively eroded granitic outcrop. Ayn Markup and Ayn Jumah have surface temperatures that range from 42°C to 46°C. The water temperature at Ayn Hurrah, however, ranges from 80°C to 85°C at the surface. At depth, the temperatures of all springs are of the order of 100°C. Flow rates of Ayn Hurrah and Ayn Jumah range from 0.03 to 0.05 m^3/s. The flow rates of other springs are much lower. The springs maintain a flow in the middle reaches of the wadi.

The springs near Jizan have two tectonised areas in a southern unit consisting of metamorphic rocks and a northern limit consisting of granodioritic igneous rocks. Ayn Khulab Quwa and Ayn Waghrah in the northern unit have surface temperatures of 78°C and 55°C, respectively. The surface temperatures of the springs in the southern unit range from 46°C to 48°C. At depth, the temperatures in the subterranean waters could be expected to be between 100°C and 150°C.

In the Eastern Region of KSA springs issue from the complicated carbonate structures of Um er Radhuma, Dammam and Neogene aquifers. Their flow is a significant factor in the discharge of ground water from storage in the area.

The importance of springs for agriculture has declined with the development of mechanisation and modern irrigation methods over the past decade. In 1945 more than 200,000 farmers depended on springs as a main source for water for agriculture. No more than 3,500 farmers now use spring water for irrigation, and those are mostly on small farms. Figure 3.2 shows Ayn Dil in Kharjarea south east of Riyadh City. The water shown here is forced to flow from a hillside, and it is used for irrigation (El-Khatib, 1980).

In certain areas, such as in Hafuf, where springs offer a reliable supply of water, development projects have been implemented in order to attain better control, usage and distribution of water by local farmers (Figure 3.3). The Ayn Juharivah is one of

Figure 3.2
Ayn Dil in Kharj, using water for irrigation

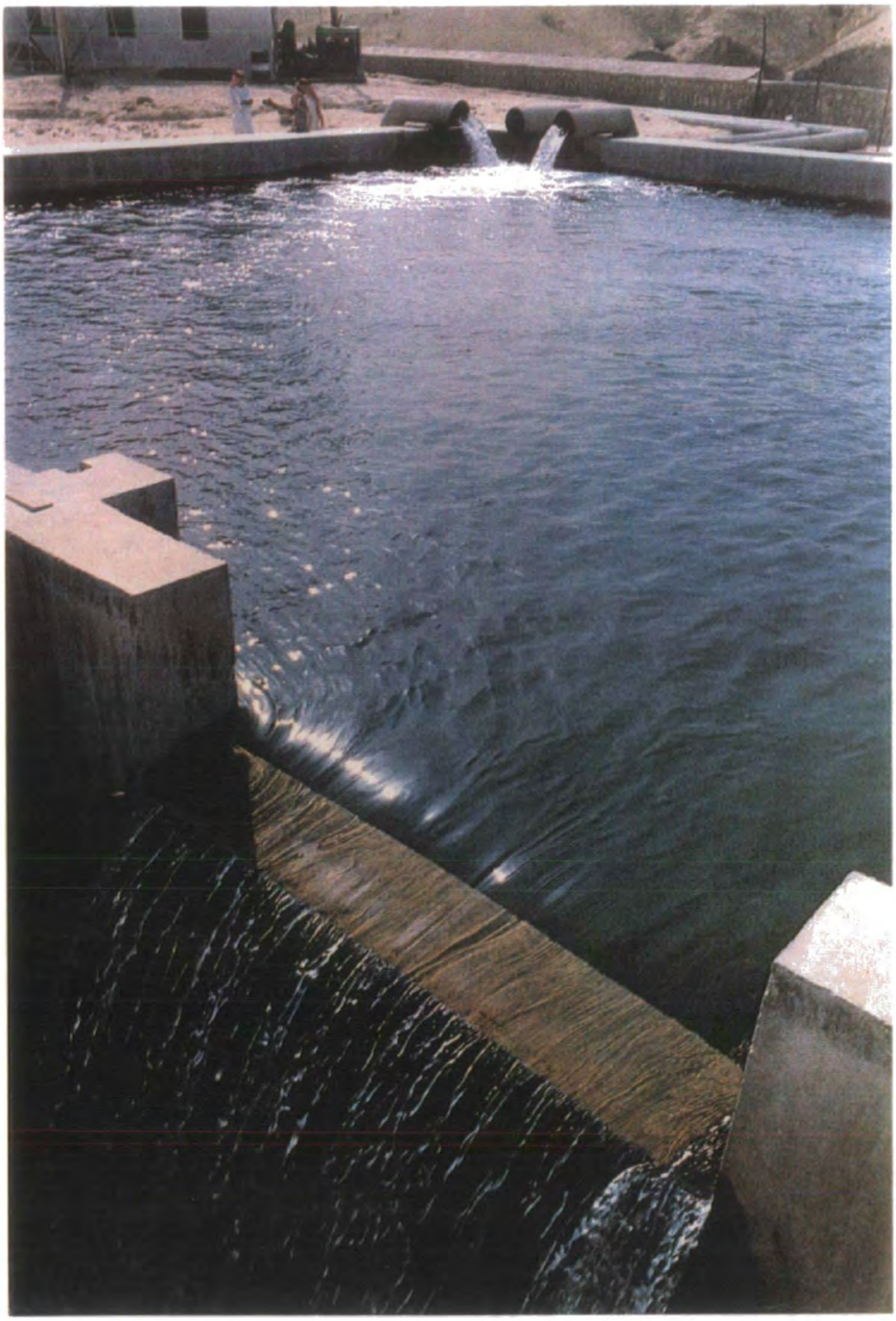
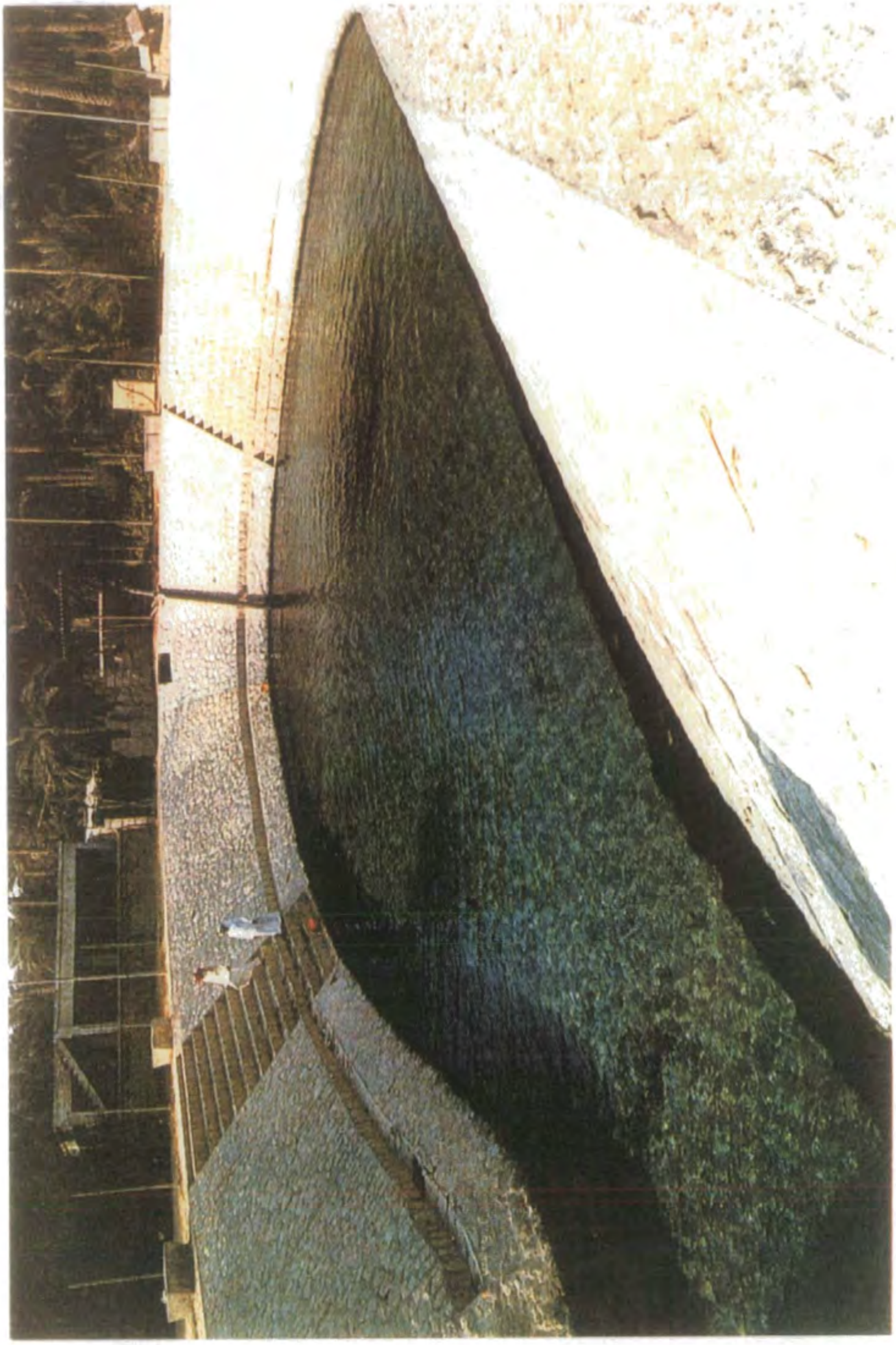


Figure 3.3
Ayn Juharivah in Al-Hasa Oasis



many artesian springs in Hassa, in Eastern KSA, and Al-aflaj in Wadi Al-Dawaseer. In other areas where water availability is limited, spring water projects were devoted to potable water only, such as Al-Lith south of Jeddah (Figure 3.4). The flow in the upper valley of the Wadi Lith coming from the hot spring located about 8km upstream.

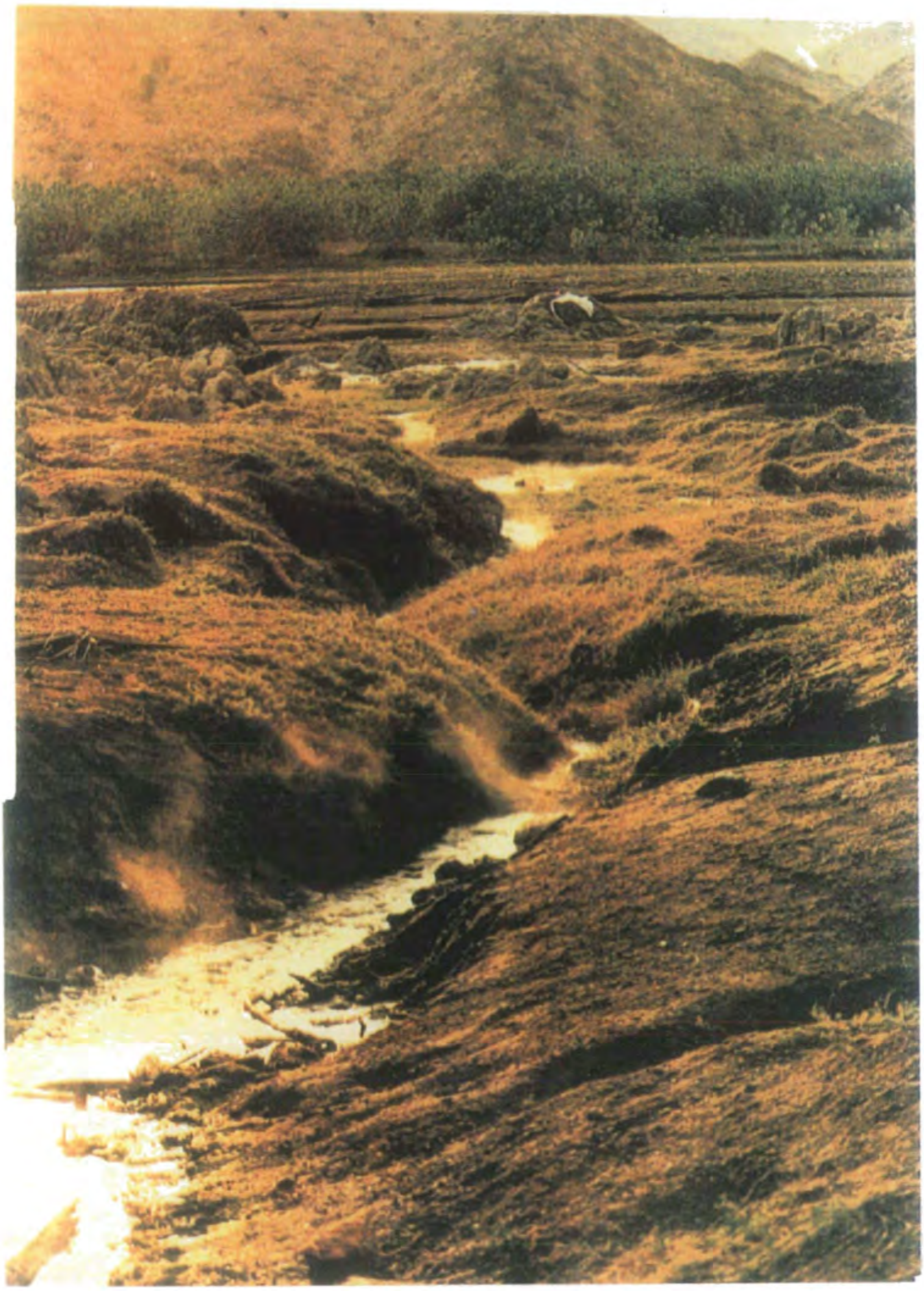
3.4 General Hydrology of the Major Wadis

This study is based mainly on the major wadis in Saudi Arabia and Tihama Asir for agricultural development i.e Wadi Aflaj, Najran, Dawaseer, Itwad, Bayish, Sabya, Jizan and Damad.

The barren mountains, with steep side ravine like wadis, offer the ideal physical conditions for intense short runoff. This is further aided by the compactness of the catchments and the short wadi courses on either side of the water divide despite the limited and intermittent rainfall. East flowing wadis are the important wadis in Saudi Arabia among those wadis wholly within Saudi territory, developing large volumes of surface flow, but their recharge potential is limited by the low storage capacity of the outwash fan deposits and the catchment area, west flowing wadis, on the other hand, have much carry runoff because of the availability of the wide and near from the mountain western Piedmont across which they spread their flows.

A distinction can be made between wadis which drain eastward towards the inland plateau of the Arabian Shield, and wadis which drain westward onto the coastal plain. The gradient of the mountain wadi course is very steep. Lower down, in the uplands, the gradient is less steep, and the wadis spread out over inland plains which are dissected by gorges through which torrential streams rush. On the coastal plain the gradient decreases still further. Nevertheless, the gradient remains steep enough for the wadi to flow to the sea in a more or less straight course. In the uplands and

Figure 3.4
Upper Wadi Lith, flow coming from the hot springs from Nakhl Nilah



especially on the coastal plains, the wadi-side population has built numerous home-made constructions to divert all or part of the flow of the wadis and irrigate the nearby cultivated land by flood spreading.

The importance of the Asir-Wadi Dawair area can be seen from Table 3.1 which shows that 340 mcm of the total runoff 775mcm is found in this region. These estimates are based on defined catchment areas varying in size of the estimated mean annual runoff. 30% is diverted for agricultural use, about 45% is absorbed in recharge of alluvial aquifers, and the remaining 25% is lost by evaporation. Surface runoff depends on the effective rainfall and is proportional to its duration and intensity. Runoff usually occurs in the dry wadis and often do not reach the sea because at high evaporation and high infiltration into the wadi alluvium. However, where rainfall is very heavy, the waters reach the sea even after an average flood. According to the operation record annually, the water rising speed is a total recorded 24.58m^3/sec about 775mcm.

Table 3.1: *Surface Water Resources in the Inland Drainage Areas*

Wadi or Wadi Group	Mean Annual Runoff	
	m^3/sec	MCMY
Asir - Wadi Dawasir Area		
Torabah	2.22	70
Ranyah	1.90	60
Bishah	4.76	150
Tathlith	0.95	30
Wadis of Southern Tuwayq	0.95	30
Asir - Wadi Najran Area		
Idimah	0.16	5
Habaunah	0.95	30
Najran	3.17	100
Taif Area		
Wajj, Al-Qaym, Liyyah, and Bissal	0.79	25
South Tuwayq Area		
Mqran	0.32	10
Jadwal Area Hamr, Ushayrahmm Aflaj Plain, remaining Catchments including Upper Jadwal	0.95	30
Aruma	0.48	15
North Tuwayq		
Northwest Aruma, Huraymila, and Salbukh	0.79	25
Ushayrahm, Sudair and remaining catchments	1.05	33
Marat formations	0.32	10
Tuwayq to Nafud	0.32	10
Meshgar	0.35	11
Remaining catchments	0.35	11
Wadi Birk-Nisah-Sabha Area		
To Nafud Sirr	0.63	20
Birk and remaining catchments from Tuwayq	0.16	5
Hawtah	0.57	18
Hanifah	0.51	16
Remaining catchments to Kharj Plain	1.30	41
Wadi Rimah-Batin		
Rub al-Khali, Nefyud and Sirhan Areas	0.63	20
Total	24.58	775

Violent floods tend to carry away the diversion works built in the beds of the wadis. Figures 3.5-3.8 show water from a flash flood, or slope water, in various wadis in Saudi Arabia which flow towards the sea, from a high gradient mountain stream, Al-Hijaz and Asir mountain.

The recorded runoff rates in the wadis are high compared to the mean annual runoff of these wadis. Volume clearly varies from one wadi to another. Compared with other wadi groups, the flow is much smaller. For instance, mean annual runoff from the Wadi Dawasir group is 10.78 m^3/sec, with a total of 240 mcm/y. Mean annual runoff in the Taif area is 0.79 m^3/sec, with a total of 25 mcm/y, as indicated in Table 3.1.

The area's annual runoff in Saudi Arabia's Wadi Najran area totals 139 mcm, with a total of 4.28 m^3/s. In the Taif area, the total annual runoff is 25 mcm, with the runoff total at 0.79m^3/s. The south and north Tuwayq area runoff totals are 4.93 m^3/s with annual runoff total of 165 mcm. The Birk, Nisah and Sabha areas' annual runoff totals are 100 mcm with the runoff at 2.17 m^3/s. The Wadi Rimah Basin area's annual runoff total is 20 mcm and a runoff total of 0.63m^3/s. The total annual runoff in Saudi Arabia is 755 mcm, with total runoff at 24.58m^3/s (MAW).

A. Wadi Aflaj

Aflaj plain is located about 330 km south of Riyadh at an altitude of 540 m above sea level. The area is very arid, with very uncertain annual rainfall of zero to 50 mm

There are some 17 villages, the largest are Layla, Al-Farcha and Al-Kharfa. Traditional irrigation has been practised since ancient times, where groundwater is available, from many open dug wells and drilled wells and from small lakes varying from 0.04 ha to 24 ha, with depths varying from 10-40 m. The sedimentary Najd is the part of the Najd region including Wadi Aflaj underlain by sedimentary rocks that outcrop in a great curved belt along the eastern edge of the older crystalline rocks.

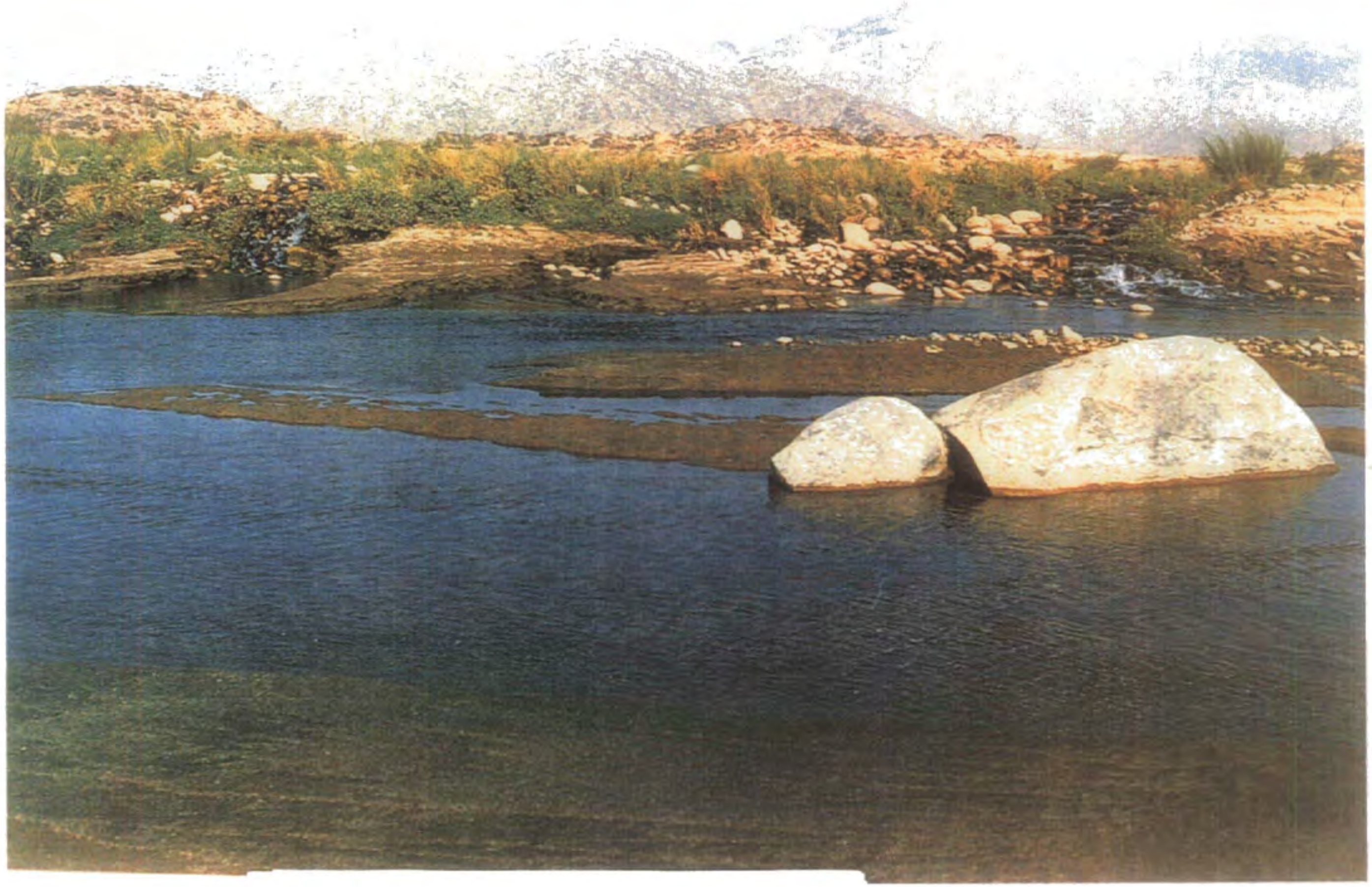
Figure 3.5
Water Surface in Wadi Duba North of Tihama

Figure 3.6

Slope Water Surface reaching Red Sea in Wadi Duba

Figure 3.7

Two Small Streams in Wadi Yiba at the Red Sea Coast



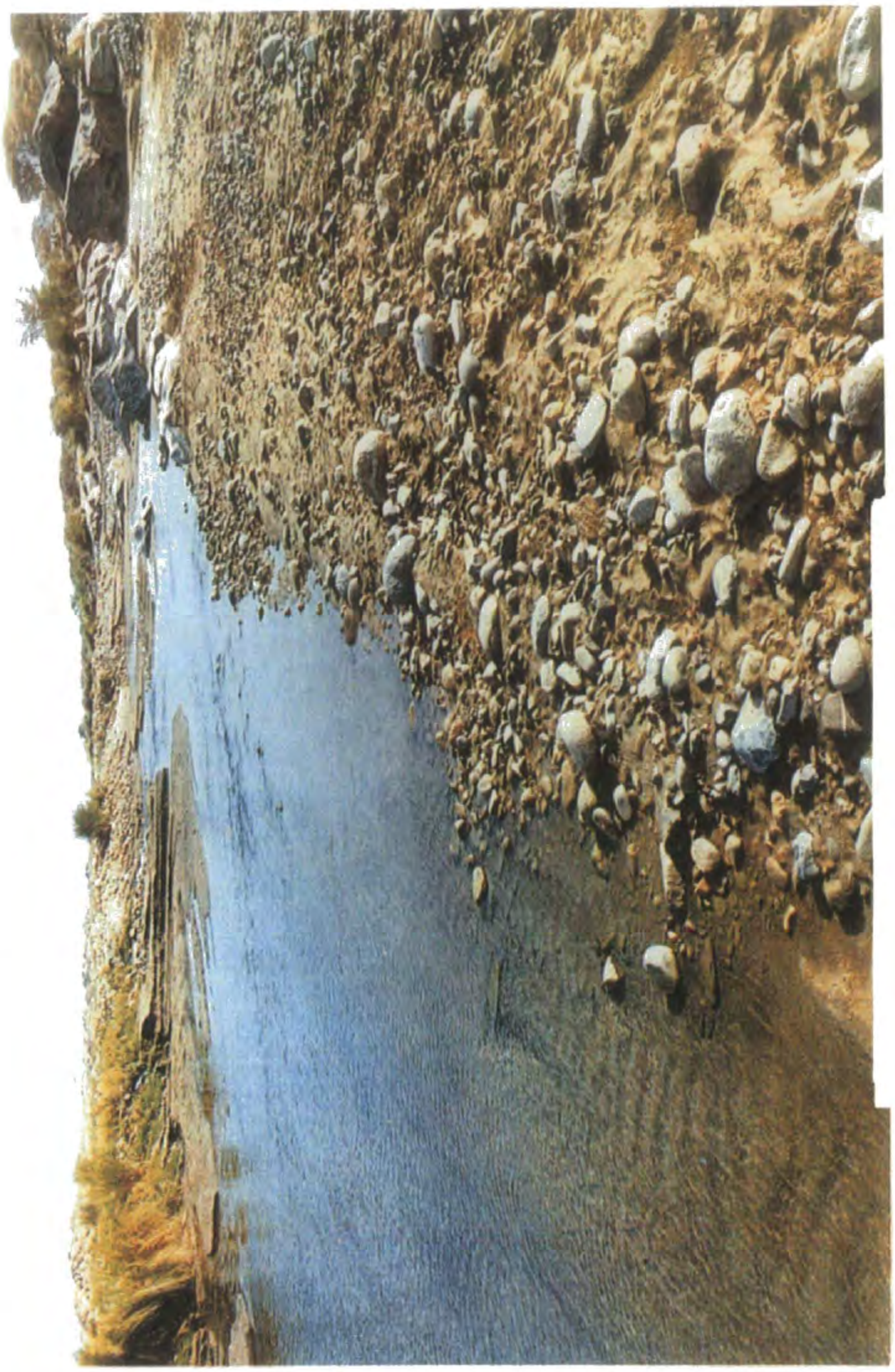


Figure 3.8

Run-off in Wadi Yiba begins on the Western Slope

The gravel fan of the wadi is large, but wide parts of it are occupied by sand. This is important, for the gravel cover, which apart from some places where it is a few metres in depth, is mostly less than a metre in depth and partly consists of only a single detritus layer on the surface. Between the channels on the flat shore area there are fine clastic sediments which are poorly sorted. The deflation of these may cause an enrichment of gravel.

The composition of the gravel is even, and consists mostly of sands and clays. Beside the sediment components of the Palaeozic to Tertiary complex of strata, there prevails above all quartz pebbles as well as magmatic and metamorphic rock components from the area of the wadi.

The open waters trending in a north-northeast to south-southwest chain some 500 m long do not show. These are groundwater lakes with a depth of greater than 20 m. The lake has doubtless developed, as its steep eastern bank has broken down. A worn intermediate terrace could indicate that the groundwater level used to be higher.

The Buwaib formation is some 45 m thick, of calcaremitic limestone with subordinate shales. It is a poor aquifer with large storage in a solution collapse zone. The ground water contains high sulphate concentrations and high calcium content.

B. Wadi Najran

Wadi Najran is located in the southwest of KSA. Though bordering the Rub-al-Khali, its climate is probably one of the best for agricultural development. The wadi drains the eastern slopes of the Asir Region to the southwest and terminates in the sand dunes of Rub-al-Khali some 150 km east of Najran.

The rock which forms the fabric of the wadi aquifer consists of the huge alluvial deposit which has been created where the wadi opens out onto the plain. This deposit consists of channel alluvium, essentially sands and of flood plain alluvium which extends alongside the wadi, and consists of finer, silty materials. The aquifer is under water table conditions in the wadi channel zone and under confined conditions in the zones alongside the wadi, as in the case of Bishah. The total annual extraction is estimated to be 64.4 mcm from 605 wells (MAW): The quality of the water is good, the TDS being 300 to 700ppm in wells excavated near the main channel of the wadi.

Under present circumstances it is difficult to provide an estimate of modal annual discharge. However, the floods in the wadi are always very frequent and it seems the aquifer may well be recharged with several tens of mcm/annum. The total amount of runoff and of groundwater extraction in the wadi was estimated by the MAW, the catchment area is 54,950 km^2, the total runoff is 75 mcm, and the annual discharge is 64.4 mcm, that runoff and groundwater extraction in the wadi.

Wadi Najran is filled with alluvial and colluvial deposits derived from the catchment area. The surface geology is predominantly Wajid sandstone of Permian age which lies unconformably on the Precambrian basement complex. Large areas of granite and metamorphic rocks of the basement are exposed where the sandstone has been removed by water and wind erosion along the wadis, particularly near the basin outlet. There are some limestone outcrops in the southern part of the basin.

The catchment area draining to El-Shata near the Outle is 4800 km^2 and Bir Khadra the easternmost limit of the area covers 5940 km^2. The topography of the wadi is mainly flat. Most of the land has a slope of less than 1%, but increases to 2% and more near the mountains.

The climate in Najran is predominantly arid with a narrow semi-arid zone and higher rainfall bordering the Red Sea escarpment.

The additional water supply required to meet the increased demand for irrigated agriculture in Wadi Najran has to come from two sources:

(a) surface flow from wadis, which is irregular, and from the storage dam;

(b) The wadi ground water, which could result in a lowering of the water level due to increased extraction.

The surface flow is regulated by the storage dam to give a direct supply of 95% reliability of up to 55 mcm/year. Table 3.2 shows the present and potential flows and water balance upstream. The amount of water presently lost and which can be conserved is approximately 18 mcm/y of which 13 mcm.y would arise from the control of wild vegetation (which is largely unproductive) and 5 mcm/y would arise from reducing evaporation downstream at Bir Khadra. This would irrigate a considerable agricultural area, and the dam was built for recharge on groundwater level, storage, consideration water regulation, distribution and flood control. The estimated quantity of ground water in the aquifer is approximately 5000 mcm upstream of Bir Khadra, and possibly ten times as much in the 80 km downstream of Bir Khadra. If 50% of the stored water were used for irrigation it would be sufficient to irrigate some 8000 ha for over 100 years. Water quality ranges from 375 ppm dissolved solids at the centre of the wadi to over 3500 ppm downstream.

Table 3.2: *Present and potential water balances mcm/year*

Inflows		Outflows		
		Present outflows	Potential saving	Potential outflows
Surface inflow past Mafija at west end of valley.	Historic cultivation	48	-	48
	Rice cultivation increase[3]	5	-	5
	Saline grass area loss	5	3	2
Total sub-surface inflows	Phreatophytes loss	12	10	2
	Underflow past Bir Khadra	28	18	10[1]
	Surface flow past Bir Khadra	13	11[2]	1
	Reservoir evaporation	-	-	1
		111	42	69
	Deficit from storage	5	5	
&	Additional cultivation		37	37
				106

1. Leaching requirement of 10% of reacharge.
2. Assumes there is a dam operated for maximum recharge.
3. Estimated to be 10% of the historic cultivation by area.

Source: MAW, Department of Water and Agricultural Development.

Groundwater is extensively used at present and is being replenished. The average rate of replenishment can be increased by controlled measures as indicated in Table 3.2, where it shows the present and potential water balance upstream of Bir Khadra. The 18 mcm/y presently wasted in wild vegetation and savings through reduction of evaporation downstream of Bir Khadra could be used for new irrigated areas. The stored water in the aquifer would be sufficient to develop a further 2000 ha of land in area and without much lowering of the water table (MAW). The percentage drawn down is estimated to be 0.15m/y. The dam was built for floodwater and storage water which is at present being evaporated downstream, and recharge much of the surface overflow into the upper wadi aquifer. The estimated quantity of groundwater in the area is approximately 5000 mcm upstream of Bir Khadra and possibly ten times as much in the 80 km downstream of Bir Khadra. If 50% of the stored water can be used for irrigation it would be sufficient to irrigate some 8000 ha over 100 years. Water quality ranges from 375ppm at the centre of the valley to over 3500ppm downstream (MAW; El-Khatib, 1980).

C. Wadi Dawasir

Wadi Dawasir is located at about 600 km south of Riyadh at the junction of Riyadh-Najran and Abha road. The area is a vast plain of undisturbed desert soil, providing an outlet to the catchment basin and into which a great part of the eastern mountains of Asir are drained.

Wadi Dawasir is the lowest identifiable active wadi channel in a big basin covering the south Shield and some areas of the sedimentary homocline. The basin is formed by several sub-basins among which the most important are: (a) Wadi Bishah; (b) Wadi Tathlith; (c) Wadi Ranyah; and (d) Wadi Turabah.

The characteristic features of this basin system include relatively organised channels in the upper reaches, plain tracks across poor and diffused local drainage and terminals and lowland which may contain sabkhas. The considerable volume flood flow from these wadis discharge into the eastward drainage of Wadi Dawasir.

a) Wadi Bishah Sub-Basin:

The main wadi runs from the highland of the Asir area in the southwest region to the lower areas of the Najid Pediplain which lies in the northwest. Here is joins Wadi Ranyah and Wadi Tathlith to form Wadi Dawasir. The basin has a large drainage area of 24,710km^2 and lies in the 400-500mm rainfall zone. It traverses the geomorphic provinces, the Hijaz Highlands, the Hijaz Northern Plateau and the Najid Pediplain. One quarter of the sub-basin area has not drainage outlet. Quartenary alluvial deposits are found as narrow strips along the wadis in the highlands of the Hijaz Plateau and as wider, often extensive, plains in the valley of the Hijaz Plateau and Najid Pediplain. In these latter areas, the deposits vary in extent from several hundred metres to several kilometres on both sides of the wadi channel, having a thickness of more than 50m.

b) Wadi Tathlith Sub-Basin:

The orientation of this basin is generally south-north. The main channel is 390km long with two main branches, Wadi Tarib and Wadi Arin, giving a total channel length of 7.075km. However, due to the large drainage area of 41,220km^2, the drainage density of only 0.17km/km^2. The basin features a large area of internal drainage, mostly downstream from the flow gauging station at Tathlith village. The northern Hijaz Plateau mostly features impervious terrain, rock outcrops or shallow area of soil. Although the extreme south has elevations around 2,400m, the average annual precipitation, 100mm, is low.

c) Wadi Ranyah Sub-Basin:

Wadi Ranyah is a long slender basin draining north-easterly. The highland areas around Biljurishi carry the runoff to the Uruq Subay. The drainage area is 12,928km^2, of which 37% has no drainage connection to the main channel. This internal drainage area comprises some 4,900km^2, of which 3,681km^2 in the north are more directly connected with the Uruq Subay. The predominant soils are Entiosols, shallow and coarse textured in rolling and hilly terrain. At the higher elevations, 2,200m, agriculture is practised on terraced lands. At the lower elevations, near the mouth of the drainage basin, there are Regiosols with greater depths, suitable for agriculture, on level to rolling terrain. Some 62% can be classified as an impervious area with the volcanic debris, the Harrat in the west, contributing to this impervious area. The basin lies within the elevation zone at 2,300m to 875m. The basin has one of the highest drainage densities per km, 0.255, in the area, indicating the potential for rapid runoff, as well as recharging the downstream alluvial deposits near Ranyah. Accordingly, the average overland flow length is 2.2km. The main wadi channel has a length of 260km with an average slope of 0.50%. In the upper catchment the channel slope averages 1.0%.

d) Wadi Turabah Sub-Basin:

Investigations were required only in the lower part area which covers 5,380km^2. The upper part has a drainage area of 12,175km^2, giving the entire basin an area of 17,555km^2. The internal drainage area is 19.8%, about half of that of the Wadi Ranyah Sub-Basin. The soils are very similar to Ranyah Sub-Basin, with the eastern side, adjacent to Ranyah Sub-Basin, also composed of the same volcanic deposits as the Harraf Newasif. The basin lies within elevations of 950- 2,300m. The terrain is rolling and hilly. The basin comprises 72% of the total as impervious area, with scanty soil cover. The drainage density is 0.209km of channel per km^2 of drainage area. The main channel traverses 270km and has an average slope of 0.45% in the upper catchment and a milder slope of 0.23% in the lower catchment. At this drainage density the average overland flow length is 2km. Wadi Turabah flows through extensive alluvial deposits in its upper catchment where the drainage is well organised. After passing through a channel construction, where there is a streamflow gauging station with cableway, the wadi once again passes through extensive alluvial deposits where local drainage is diffused. The wadi ends in the terminal lowlands of the Uruq Subay, where vast riverless sand cover absorbs the remaining flow.

Water Resources:

Water resources in the areas are made up from rainfall, runoff and groundwater. The main supply of water is from wells sunk in alluvial deposits and weathered rocks and to some extent from flood water. Primitive practices have been evolved to make use of surface water. These practices include terraces, water spreading cisterns and infiltration galleries. Over 90% of the rainfall in the area is lost to evaporation. Runoff ranges between 3-8% of the rainfall. Groundwater recharge rates between 2-4% of the rainfall and it infiltrates through the wadi bed alluvium. The rainfall on the terraced areas of 270km^2 is estimated at 7.3mcm/y and that for agriculture of 170mcm/y (MAW).

Groundwater resources in the area as a whole are relatively meagre and abstraction should never be greater than the recharge for any significant length of time. The main problems of groundwater development are related to the small aquifer size and the nature of the recharge. Salinity problems in these aquifers can develop rapidly when such groundwater is used for irrigation. there are some 18,542 wells in the area with water having less than 1,000 total dissolved solids (TDS) (MAW). However, open hand dug wells are sometimes subject to bacterial surface pollution.

Wadi Dawasir Step-Fault System:

The Wadi Dawasir Step-Fault System is some 80 to 100km wide and borders the southern Najid uplift to the south. It is characterised by a great number of parallelled faults with a typical lower Paleozoic northwest-southwest trend. The area covers the southern and more important part of the fan-shaped Wadi Dawasir catchment, the drains of the Pre Cambrian formations from the Asir escarpment ridge in the south, southwest and the watershed with Wadi Najran in the south. The sedimentary cover of the area reaches a total thickness of 4,000km. Sedimentation conditions were favourable to the formation of porous rocks and such have been found to occur frequently in geological time. The deposition of coarse clastic rock, which constitute the water bearing horizons, was general so that new aquifers cover a considerable extent of the area and occur exclusively in sandstone formations which, taken as a whole, can be considered homogeneous and is a topic. The boundaries of the aquifer are quite clear in the vertical sense. The thickness of the aquifer is very uncertain at Wadi Dawasir (some 400 to 440m) (MAW) and to the south the thickness increases, while to the west it becomes thinner. The aquifer may be considered as a single hydraulic unit with fairly homogeneous lithology. Artificial discharge from the aquifer is limited at present to the Khammesin in Wadi Dawasir area. An estimated 10 mcm/y is extracted for irrigation from pumped or free flow wells completed in both the unconfined and artesian part of the area. The quantity of water discharged in Wadi Dawasir is possibly greater than the amount of recharge, 110mcm/y (MAW). The hydrological situation of the Wajid aquifer is very complex. It is tentatively estimated that there are at least 100,00 mcm of water stored in the unconfined part of the aquifer.

The quantity of water which can be mined from storage is very considerable. It can also be stated that the potential economic yield of the Wajid Aquifer in Wadi Dawasir area is several hundred mcm/y. With regard to recharge by underflow, the Wadi Dawasir, which commences after the confluence of the major drainage system, is the only one to collect groundwater, moving eastwards as underflow from the Shield area wadis. The recharge which occurs in the Wadi Dawasir tributaries, and which locally causes a considerable rise in the level of the water table, may be estimated to be 6.5% of the rainfall over the various catchments. Salinities of water in the main aquifers, namely that in Wadi Dawasir, are extremely variable. All gradations are encountered from a maximum of 24,000ppm total dissolved solids (TDS), to a minimum of 794ppm. The major part of the water stored in Wadi Dawasir alluvium is highly brackish. However, where upward leakage from deep aquifers occurs, there are well defined zones of low salinity.

The water which comes from the Crystalline Shield are already highly mineralised and the salinity increases further until it reaches a maximum of 24,000ppm at Al Atwa at the outlet of Wadi Dawasir, south-east of Sulayyil. It is assumed that the increase in salinity is caused essentially by evapo-transpiration losses occurring particularly in the extensive sabkha of the Wadi Dawasir between Kabkabiyah and Sulayyil. The aquifer in the Wadi Dawasir gravels is the only one developed to any great extent in the whole of the area. Hence, in comparison with other aquifers, the amount of artificial discharge is by far the highest and is estimated at 35mcm/y (MAW). It is concentrated in Al Wadi, Tamrah-Hayran and Sulayyil and is the most important for extraction. It is worth noting that during the last 12 to 17 years groundwater extraction has increased considerably because of the introduction of engine-driven pumps. The effect of this is that the salinity of the water has increased in various localities, especially Sulayyil.

The amount of water stored in the Dawasir alluvial deposit can be roughly estimated, by the MAW, to be 15 billion m^3. Unfortunately, the volume of good quality water is only a small proportion of that amount and is located in the area of upward leakage from underlying aquifers and in the areas of indirect recharge from floods in the tributaries.

In all these wadis (and normally following present drainage lines) the valley depress-ions are filled with thick gravel accumulations seldom appearing as lateral fluvial terraces. They are composed of course sand and fine gravel in Wadi Bishah, course sand and fine gravels in Wadi Tathlith, course sand in Wadi Ranyah, coarse sand and fine gravel in Wadi Rurabah and course sand and gravels in Wadi Ad Dawasir. In all of these cases, gravels are polymictic with a variety of crystalline rocks and some places sedimentary pebbles (Wadi Ad Dawasir limestone pebbles).

There are several small oases along the northern edge of the wadi where about 2000 ha are irrigated mainly from traditional and dug wells 5-25 m deep in shallow alluvium. There are three main aquifers in this area:

(1) Wajed Aquifer, which consists of sandstone of fine to coarse grained texture and which outcrops over a large area. It has the most promising potential for irrigated agriculture, salinity varies from 750 to 1000 ppm.

(2) Dhrumu Aquifer, consists of fine to coarse gravel sandstone interbedded with a layer of shale. The aquifer appears less extensive and thinner than the Wajed Aquifer. Its water is less suitable for irrigated agriculture and contains a high chloride content.

(3) Alluvium Aquifer of the Quaternary formations. This consists of surface deposits of coarse sand with minor amounts of finer grained gravel and may contain silt and clay. The water table along Wadi Dawasir is at relatively shallow depth and the quality is poor, with dissolved solids content varying from 800 ppm to over 24,000 ppm.

The surface runoff promoted by the copious rainfall, in connection with the lowering of the general base level of erosion, has led to a distinct linear erosion. This is evident not only in the dissection of the basalts but also in the mostly filled up erosion channels of the ancient drainage system.

The surface morphology in the area covered by the dunes never indicates the wadi system.

Table 3.3: *Surface Water Resources in the Red Sea Coastal Area*

Wadi or Wadi Group	Mean Annual Runoff	
	m^3/sec	MCMY
Khulab	0.95	30
Jizan	2.38	75
Dhamad	1.90	60
Wasi, Shadan, Qara, Akkas, and Baysh	3.17	100
Itwad	0.95	30
Shafqah and Hali	3.49	110
Tayyan and Yiba	1.90	60
Qanuanah	1.59	50
Iyar and Lith	1.43	45
Fatimah	1.43	45
Khulays	1.74	55
Rabigh	2.06	65
Khaybar and Tubjah	1.11	35
Total	24.10	760

Tihama Asir is a steppe-type region of the coastal plain which stretches some 300 km along the Red Sea coast and is some 30 to 40 km wide. It is bounded by the Asir mountains from the east, by the Arab Republic of Yemen from the south and the Red Sea from the west. Table 3.3 provides an assessment of runoff, of which only a fairly small portion of those flows produce any beneficial effect. Mean annual runoff from the wadis in the Red Sea Coastal Area (including Tihama Asir), totals 24.10 m^3/sec from an annual 760 mcm/y. The Tihama side of the Asir mountain range (36,730 km^2) enjoys 85% of the total runoff, while the wadi quadrangle side (102,090 km^2) has only 15%. Data regarding the water level of wadis at many locations, along with details of runoff in the region, are available from the operation records of the wadis. The behaviour of water in these wadis clearly shows the runoff rate in the area, as in Table. The plain is intersected by several wadis that run east to west from the Asir Mountains to the Red Sea coast (Figures 3.9 and 3.10). For example, the runoff from Wadi Shafqah and Wadi Hali is 3.49 m^3/s (110 mcm/y) (MAW). This can be attributed to the runoff from the mountains after rainfall. Runoff from the Wadi Baysh group is 3.17 m^3/s (100 mcm/y). Wadi Jizan and Wadi Rabish account for 2.38 m^3/s (75 mcm/y) and 2.06 m^3/s (65 mcm/y) respectively. Wadi Damad and Wadi Yiba account for only 1.90 m^3/s (60 mcm/y) each, because Wadi Damad receives water from Wadi Jizan (downstream), and Wadi Yiba experiences low rainfall, as do Wadis Qanuanah, Lith, Fatimah, Khaybar and Tubjah. Wadis Khulab and Itwad are branches of other wadis. Wadi Itwad branches from Wadi Bysha, and Wadi Khulab branches from Wadi Liyah (upstream). The inflow into wadis differs from the runoff generated from precipitation over the catchment area of upstream wadis. This outflow indicates that the mean annual inflow can be used for managed outflow uses as follows:

(a) 50% of the mean annual inflow to be equally distributed between the 12 months of the year, and may be utilised for perennial irrigation by flowing through closed conduits;

(b) the remaining 50% of the mean annual inflow to be released during one month from mid July to mid August, and may be utilised for spare irrigation only once every year by flowing through the wadis' natural channels.

Runoff from flash flood causes turbulent flow in the Wadi Habaunah at Husayniah after rainstorms, and gives rise to the main wadis in Tihama Asir, such as Wadi Jizan and Wadi Baysh. These can be divided into groups for the purposes of studying the surface water system.

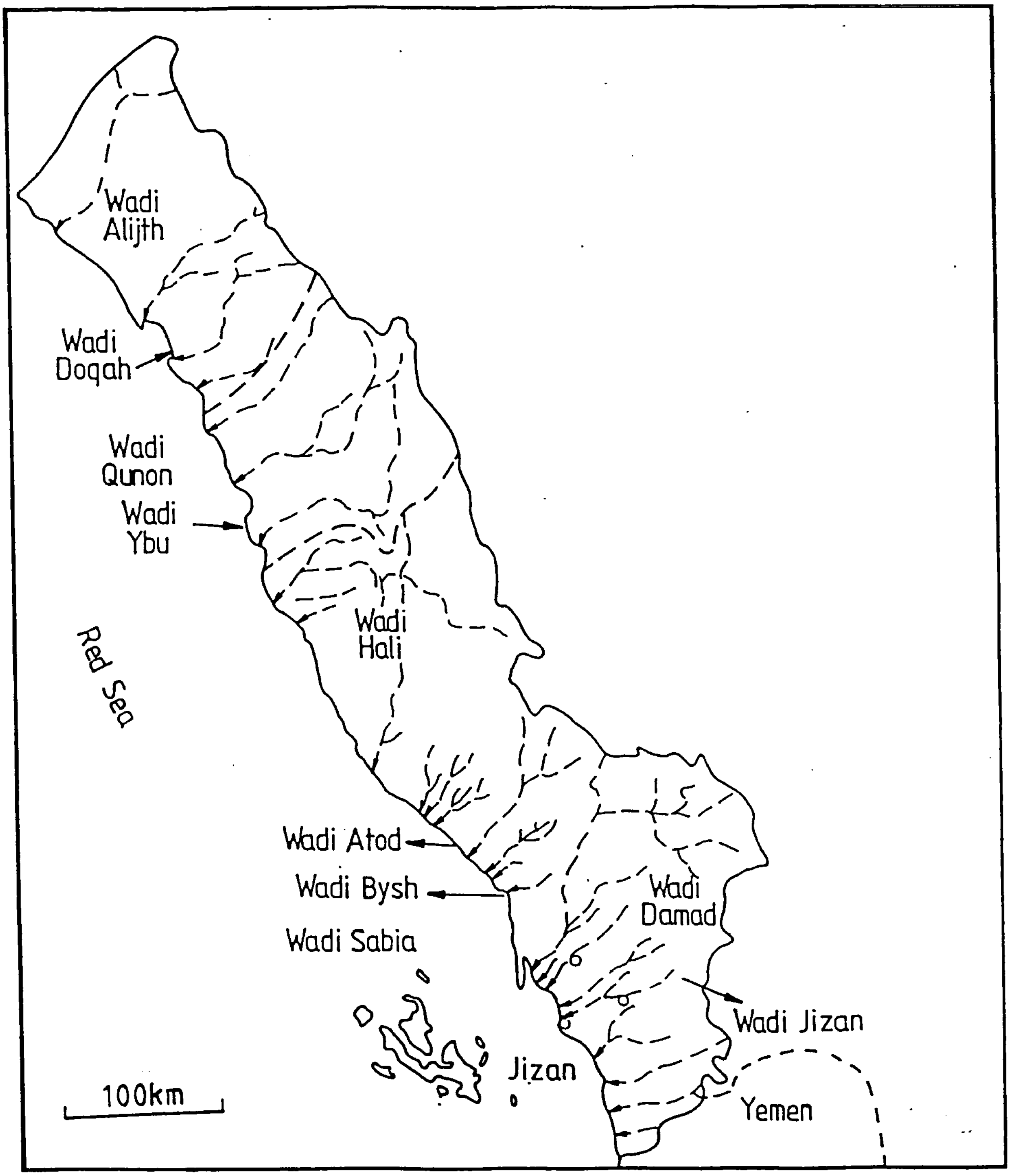
A. Wadi Itwad

Wadi Itwad is an important water course of the study area. Although its catchment basin is one of the smallest in the 1984 study, it can still offer insight into an

Figure 3.9

Water from a flash flood in Wadi Habunah

Fig. 3.10 The Surface Water System Discharge



interpretation of the hydrological regime by means of modelling. The rain gauge used in the simulation is in the wadi bank. The Wadi is north of Wadi Bayish.

Wadi Itwad is one of the Tihama Asir wadi drainage systems for the southern Asir highlands runoff away to the Red Sea, and for the coastal plain. The base is formed, so far as is visible, by the steep-faced stones of the Dyke formation. Only in the western part of Wadi Itwad are the rocks of older age, and the wadi bed is made of sand and is rather wide. The middle terrace follows it on the left side, flanked by the main terrace surface, which is somewhat set off and widens to the south. On the right side of the wadi there are broad remnants of the lowest terrace with eolian and fluvial sands and silts.

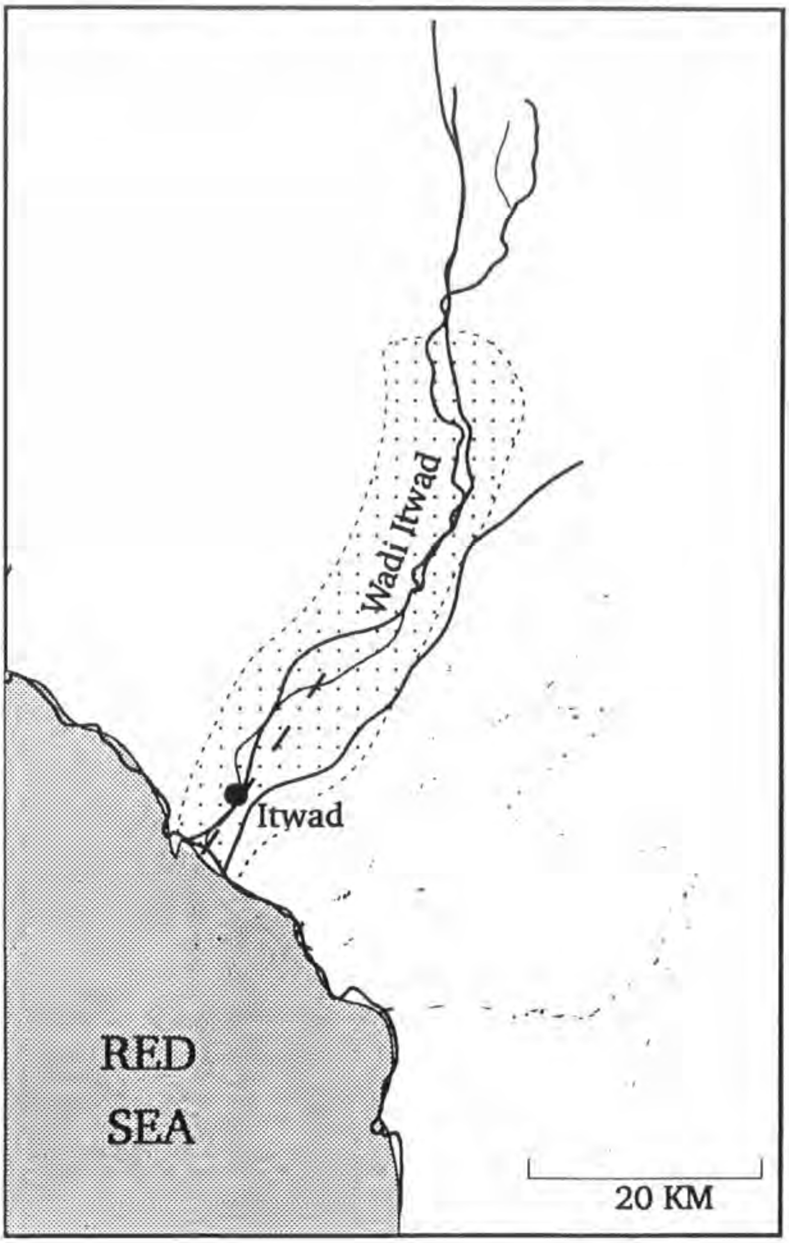
The sides of the valley are rocky. On both banks an alternation of greenstone and schist series is found.

The catchment amounts to only about 980 km^2; the annual inflow of frequency 0.5 is estimated at only 17 m^3. The exceptional flood is estimated at 4000 m^3/s.

The loose sediments and underlying disaggregation area of the basement complex, which is 2-5 m thick and geophysical differentiable, are to be viewed as potential groundwater aquifers. The sandy, silty upper layers of the flood-plain reach to sea. The groundwater from the wadi on the slope thus contrasts distinctly with high evaporation effects of surface water. In the wadi, the sampling location is the upper water outlet from a terrace slope.

The potentially irrigable surface is 2,900 ha according to agricultural investigation, where the area which can be irrigable rationally by the Wadi Itwad is only 900 ha with a peak flow of 1.15m^3/s. The elongate irrigation area on both the right and the left banks, of course considerably increases the length of the principal and secondary channels (Figure 3.11).

Fig. 3.11
Wadi Itwad, Surface Water System Drainage



B. Wadi Baysh

Wadi Baysh is one of the most important wadis of Tihama Asir. Its main axis runs northeast to southwest and is bordered on the north by Wadi Itwad, on the east by the rocky outcrops of the Asir foothills, on the south by Wadi Sabya and the road to the town of Sabya, and on the west by the Red Sea coast.

The catchment basin of Wadi Baysh is some 4312 km^2 rising in the Asir Mountains and discharging to the Red Sea. The wadi is long, being from 180 to 900 m and some 2200 m above sea level. It is mainly pre-Permian gneisses and schist with more recent quartzites and basalt flanking the sandy coastal plain.

Surface water in Wadi Baysh, and other wadis, after floods in the form of run-off lasts between 12 to 18 hours (see Chapter 2).

The irrigable surface, drawing water resources from the wadi, is estimated at 15,000 ha. Almost all the irrigable land is on the right bank. The area to be irrigated is compact, which should make it possible to reduce the length of the main channel. On the other hand, the use of all the suitable land will probably necessitate important development work involving levelling.

The rate of flood discharge is about 11,000 m^3/s.

In the present context this relationship is exhibited by the ratio of run-off to rainfall, run-off being that part of the total rainfall which is allowed to run freely on the ground at any place. This study found this ratio to stand at an annual average of 0.44 for Wadi Baysh. The range of difference between the maximum and minimum annual ratio obtained is rather large, reaching 4.8 for Wadi Baysh. Table 3.4 shows the annual average discharge recorded and simulated runoff in Wadi Baysh, that peak flow was different in the years 1981-82-84 which had a lower runoff than in other years (36.654, 35.099 and 37.987mcm respectively), but in the years 1986-87-89-90 it had a higher cf 1973 + 1981 – completely

Table 3.4

Discharge Between 1973-1984 at Wadi Bysh

mcm/y

Drainage Area 4713 km							Altitude 200 m								
No	Station		JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	ANNUAL
1973	Wadi Baysh		116.1	18.5	11.5	29.7	32.3	3.9	112.15	98.15	60.97	4.97	6.1	36.04	45.797
1978	17 34 40	Lat.	6.78	0	186.41	70.83	157.87	91.03	179.54	149.18	78.2	49.75	17.82	28.57	87.146
1979	42 37	Long.	23.15	34.35	36.53	306.44	31.65	43.47	32.82	292.09	32.8	28.13	14.116	14.38	76.88
1980			15.49	10.65	75.03	49.97	55.31	35.5	59.34	60.69	61.69	44.36	46.74	10.8	45.386
1981			57.59	7.44	7.59	32.34	58.29	35.17	43.5	43.6	32.04	45.27	57.86	3.41	36.654
1982			91.86	31.44	22.31	19.64	28.01	12.16	36.28	81.94	85.02	24.49	12.08	10.87	35.099
1983			47.28	33.07	33.12	41.57	83.63	44.56	36.12	57.12	37.12	16.84	6.43	26.63	40.096
1984			8.66	15.00	13.13	44.94	89.99	56.15	112.22	57.03	18.55	13.13	3.4	7.47	37.987
1985			4.72	2.78	245.74	68.74	313.39	93.17	113.03	80.05	97.92	56.48	16.49	15.73	95.748
1986			69.98	307.28	154.83	216.56	85.99	74.57	84.43	142.98	83.57	68.91	54.69	58.52	121.17
1987			22.51	285.66	140.11	372.92	202.15	203.51	180.94	144.57	81.6	38.07	35.7	39.1	150.94
1988			38.11	33.37	32.99	36.22	184.75	99.78	115.33	83.21	41.3	26.35	25.5	44.88	65.85
1989			74.62	42.88	45.18	215.54	143.9	115.2	173.99	151.5	70.69	78.96	86.51	75.74	110.04
1990			0	0	41.97	386.53	189.12	102.62	179.89	180.16	82.4	3.48	0	16.39	102.141

runoff (121.17, 150.94, 110.04 and 102.141mcm respectively), the runoff over this period came from the Asir Mountains. The arithmetic mean of the annual inflow for the 14 year period was calculated, runoff figures were calculated for the same time periods. The data shows variations between months of the same year, as well as for the same month in different years.

Only when the comparatively large volume of runoff of a particular rainy year is set against that obtained during years of very low flow, can the actual mean annual contribution be identified. Taken as a whole for the gauged catchment based on available runoff data, the average runoff for the catchment is 1,050,744mcm/y, of which a part only ends up as recharge to the groundwater.

The runoff values are consistent, for Wadi Baysh is mainly within a different rainfall distribution regime due to the extension of a great portion of its watershed more easterly, where the precipitation is less.

The calculation is for total rainfall over the basin of the Wadi Baysh, despite the fact that the former lies on the leeward side of the summer monsoon which furnishes the greater part of the annual rainfall over this part of Saudi Arabia.

The fresh water bearing layer has been penetrated by drilling. At the drilling site it has a thickness of approximately 60 m and consists of layers of clays, sands and gravels. The gravel layer has a total thickness of 20 m. Groundwater channels may connect with diversion channels, through which flood water from Wadi Baysh is diverted to flood irrigated areas to the west of Wadi Baysh. In fact, there are freshwater channels through which floodwater from Wadi Baysh is diverted to flood irrigated areas to the west of Wadi Baysh. The freshwater channels which have been revealed by the geoelectric survey underlie these diversion channels. Therefore, it would seem to be evident that the groundwater channels are, at times, fed by percolation from the overlying surface flood. Figures 3.12, 3.13, 3.14 show views of Wadi Baysh, through which flows flash flood water, where the bank has been reinforced to prevent undermining of the road. They also show vegetation on the wadi bank and the surface water system drainage after rainfall.

C. Wadi Sabya

Wadi Sabya is an important wadi. It rises in the Asir mountains and crosses South Tihama to discharge its water in the Red Sea. The catchment area is about 627 km^2 and some 2000 m above sea level. Wadi Sabya is bordered on the north by Wadi Baysh, in the east by the Asir Mountains, on the south by Wadi Dhamad, and on the west by the Red Sea coast (Figure 3.15).

Wadi Sabya plain lies in an area with a hot arid climate, although this is sometimes moderated by monsoons from the Arabian Sea. It experiences very high temperature, exceeding 40°C in May-July and temperature as low as 20°C in December-January. Wadi Sabya rises in the Asir Mountains, the heavily faulted western edge of the Arabian Shield. The catchment area consists of an upland region of mainly Precambrian schists and an alluvial plain region of mainly Quaternary age bordering the Red Sea.

The soil of Wadi Sabya is similar to that of Wadi Dhamad and Wadi Jizan. They are sandy and fine sediments deposited by many years of flooding making a deep soil with a high capacity for water retention.

The northern drainage channel is detectable only in its lower course. Therefore, its direction cannot be determined.

However, in the area of a well the freshwater-bearing layer has a minimum thickness of 55m, and consists of an interbedding of clays, silts and gravels. The gravels, divided into four layers, have a thickness of 15m. It passes through Sabya and provides the

Figure 3.12

Wadi Baysh near Baysh Town, water flows in Tihama Asir

Figure 3.13

Wadi Baysh near the north-south road in Tihama Asir (35 km from Jizan City)

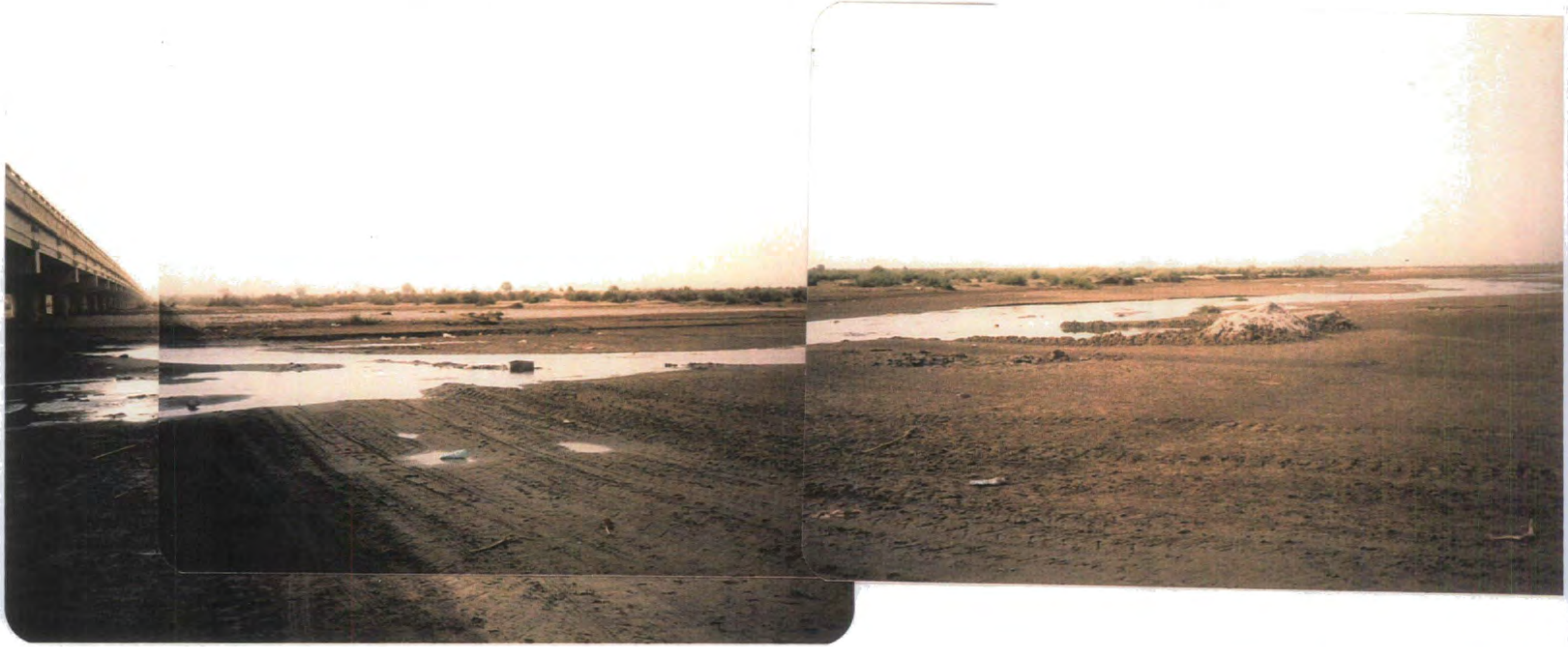


Fig. 3.14
Wadi Bysh Surface Water System Drainage

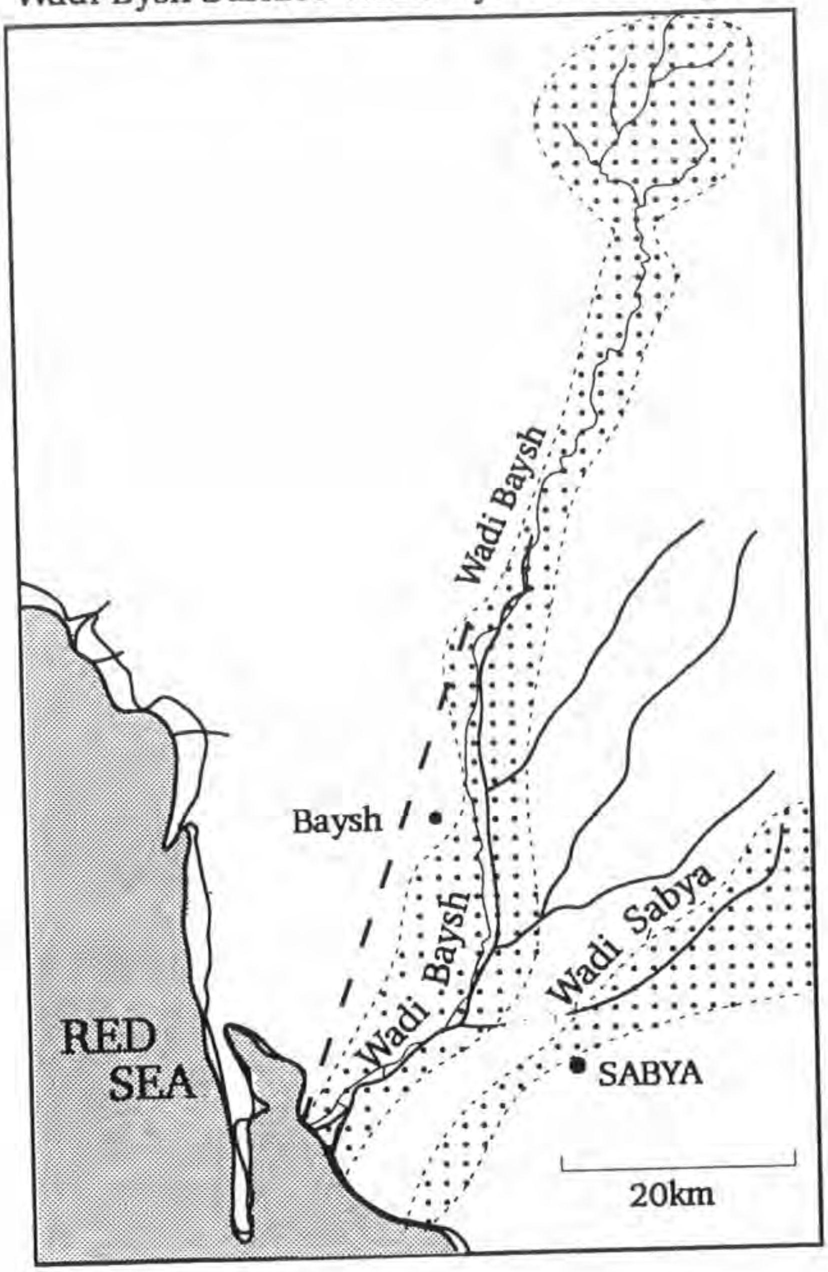
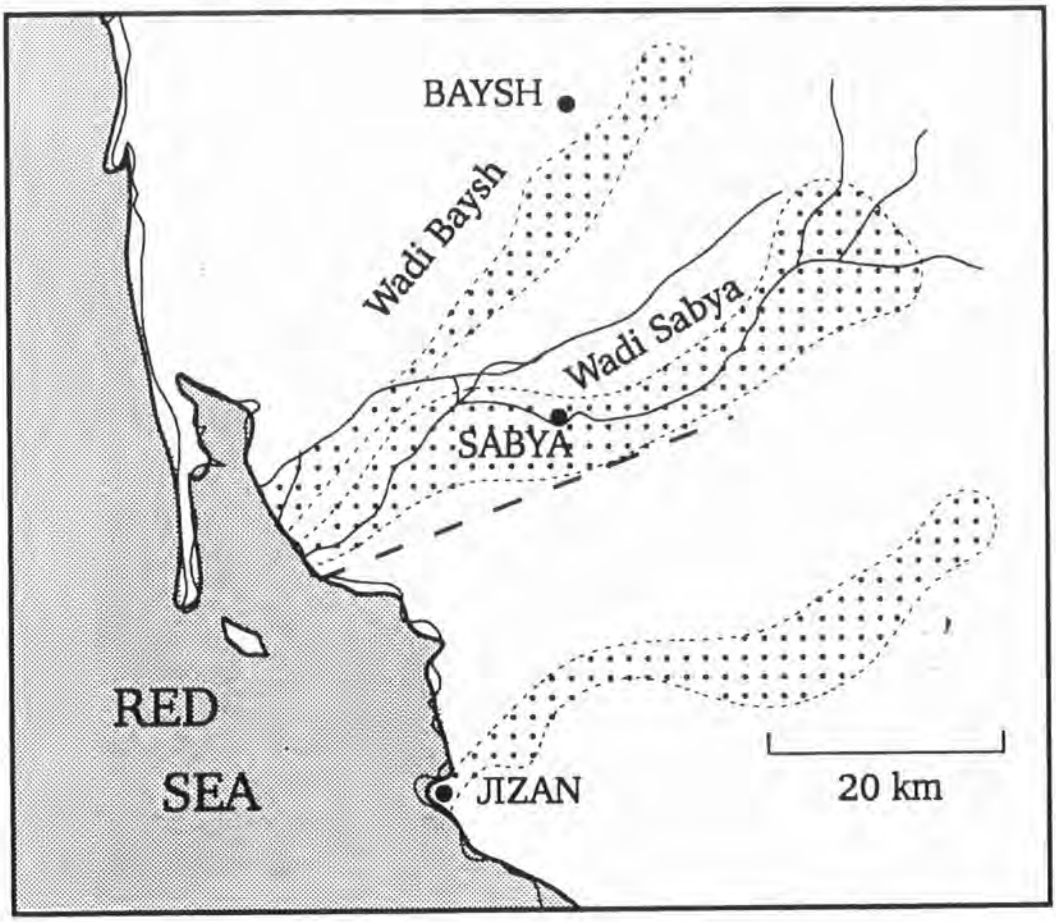


Fig. 3.15

Wadi Sabya, Surface Water System Drainage



drinking water supply for this village. The freshwater-bearing layer thickness increases to 100m. North west of Sabya, however, the depth is only 30m. In its lower course the fresh water flow joins the drainage channel of Wadi Baysh.

The water in the wadi experiences little or relatively strong evaporation. The water supply from the wells is practically free of tritium and, therefore, essentially consists of water of a mean age of more than 20 years. However, it consists of groundwater formed by precipitation and runoff.

Groundwater resources of Wadi Sabya are estimated to be about 10.3 mcm per annum, and are in general suitable for both irrigated agriculture and for domestic use.

Annual water flow of the catchment area is 59 mcm and the median annual flow available is 50 mcm (see Chapter 2).Figure 3.16 shows Wadi Sabya, a garden, vegetation and moist soil after runoff.

D. Wadi Jizan

Wadi Jizan is located in the southwestern region and runs in an almost east-west direction on both sides of latitude 17°N. It rises in the Asir Mountains at an elevation of about 2,500 metres above mean sea level at longitude 43°30'E and empties into the Red Sea at longitude 42°30'E, north of Jizan City after travelling about 120 km (Figure 3.17).

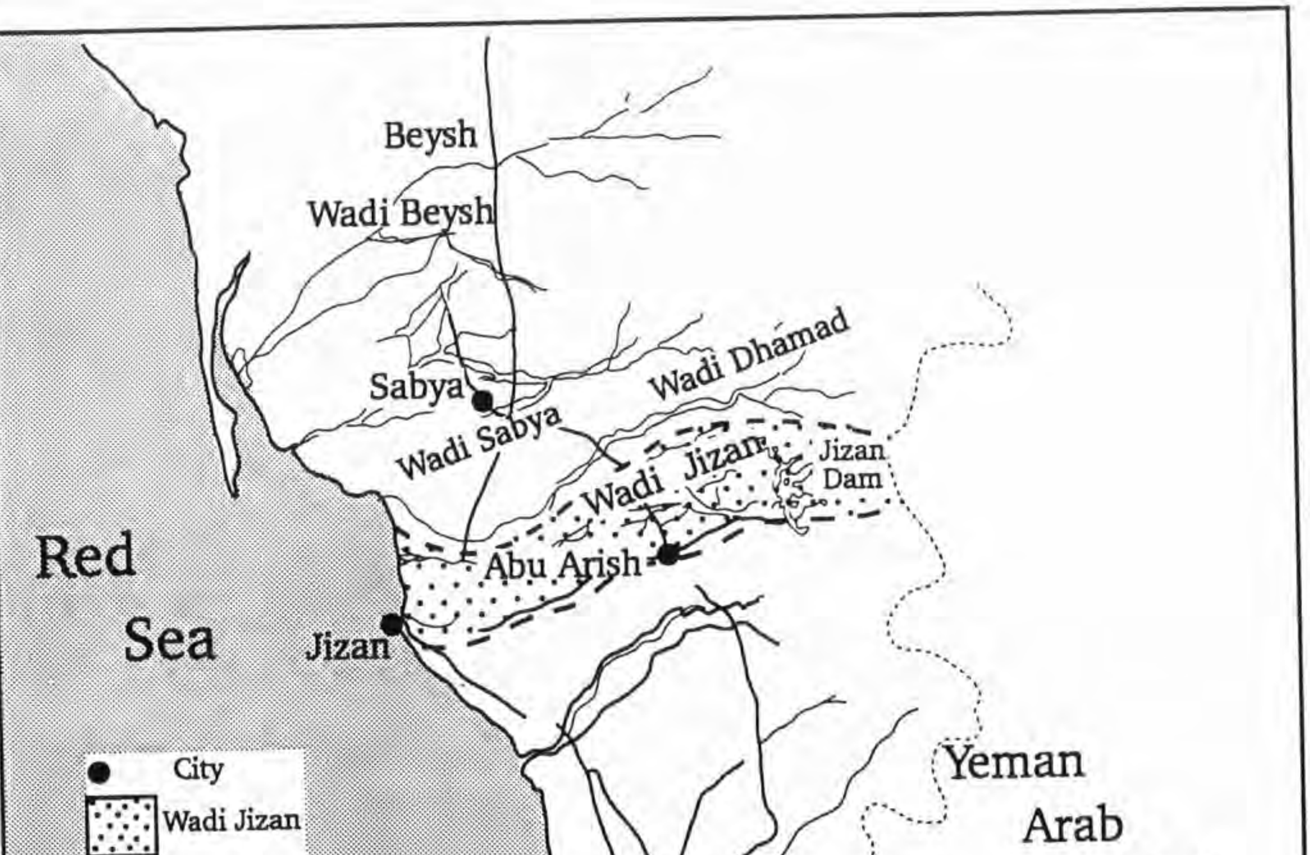
Wadi Jizan is narrowed by the basalt eruptions in the transitional area between mountains and coastal plain. The wadi originally was uniformly wide, but in this section was forced to create a bed, in canyon-like places. This caused repeated shifting of individual small channels, as may be seen in a tributary south of the Malaki Dam.

The basin of Wadi Jizan can be divided into three distinct regions according to elevation, rainfall and agricultural practices. The mountainous region over elevation

Figure 3.16

Wadi Sabya, garden and soil in sandy loam

Fig. 3.17. Wadi Jizan, Surface Water System Discharge.



500 metres has a mean annual rainfall of about 450mm. The region of elevation below 500 metres and above 200 metres (below which is the lower plain region), has a mean annual rainfall about and below 200mm. These first two regions are within the catchment area, and support little agricultural activity.

The third region comprises the area of intensive agriculture mainly under spate irrigation downstream of the dam. This wadi was the first wadi in Tihama Asir to have a dam (see section on dams in this chapter). Table 3.5 gives the total monthly and annual discharge values for the 14 year period into Wadi Jizan reservoir in million cubic metres (mcm). The years 1978-1991 had a lower runoff than other years because local rainfall during these years was insufficient to run into the wadi. The rainfall and runoff was not local, but came from the Asir Mountains. Knowledge and understanding of the surface water, which comprises the inflow into Wadi Jizan reservoir as a function of rainfall and the inter-relationship between surface and groundwater, are essential for planning the irrigated agricultural development of the area, the annual discharges between 1978-1991. Runoff in some years has been low, e.g. 1978 (24.86 m^3), 1990 (26.602 m^3), but in other years there was a higher discharge, between 40.217 m^3 to 98.38 m^3. Run off, strictly, is the ratio between amount of discharge at a certain control point resulting from a rainfall over the catchment area upstream, and the amount of rainfall. Whilst runoff may be constant for many basins. runoff can vary with the amount of rainfall. It is of importance that cautionary and control measures are carried out for higher rainfall values than for lower rainfall values since the former may result in disastrous floods. Figures 3.18, 3.19, 3.20, show Wadi Jizan, the residual flow down a dam, and the water lake after rainfall, with vegetation growth after rainfall over the area.

The government of Saudi Arabia has selected Wadi Jizan as a pilot area for agricultural development based on improved and full utilisation of its water resources to

Table 3.5
Discharge (runoff) at Wadi Jizan Between 1978-1991 mcm/y

Drainage Area 1200 km . Altitude 178 m

No	Station	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	ANNUAL
1978	Wadi Jizan of	0	0	0	0	27.59	5.44	106.55	42.53	33.1	28.16	29.66	14.82	24.86
1979	Malaki	3	174.91	1.85	143.57	21.53	134.82	394.73	73.09	15.03	15.03	0	8.8	83.859
1980	17 03 Lat.	6.83	7.17	6.94	190.99	12.5	42.14	186.15	187.17	75.55	8.1	6.94	8.8	63.929
1981	42 57 Long.	5.56	3.01	2.67	98.28	51.81	40.44	64.07	119.01	71.01	72.67	137.62	0.46	57.631
1982		5.56	0.23	56.27	30.12	134.14	0	33.85	50.37	37.99	347.53	80.57	6.25	67.61
1983		151.9	71.63	17.24	0	87.28	13.5	561.87	104.81	46.49	16.43	63.23	4.98	98.38
1984		57.23	0	5.44	0	9.61	13.08	10.18	250.97	162.06	78.41	2.43	86.31	58.39
1985		8.45	0	0	23.04	23.95	27.29	34.06	202.6	65.46	98.73	17.12	1.15	43.359
1986		0	0	612.9	76.31	157.17	3.12	49.16	131.6	53.08	13.08	0	2.43	95.04
1987		257.62	22.96	0	18.52	161.2	33.95	73.37	61.88	80.57	83.98	9.37	114.68	79.34
1988		7.52	46.09	74.23	90.23	83.99	17.94	30.71	85.075	1.79	6.37	0.37	0	38.391
1989		0	0.14	0	9.545	60.8	9.02	9.56	57.23	81.04	26.663	0	54	26.602
1990		23.31	2.64	19.695	268.36	146.54	10.12	26.35	87.08	101.71	3.27	6.53	0	60.149
1991		0	5.99	29.82	166.02	22.73	8.16	19.62	93.37	52.09	44.65	13.42	10	40.217

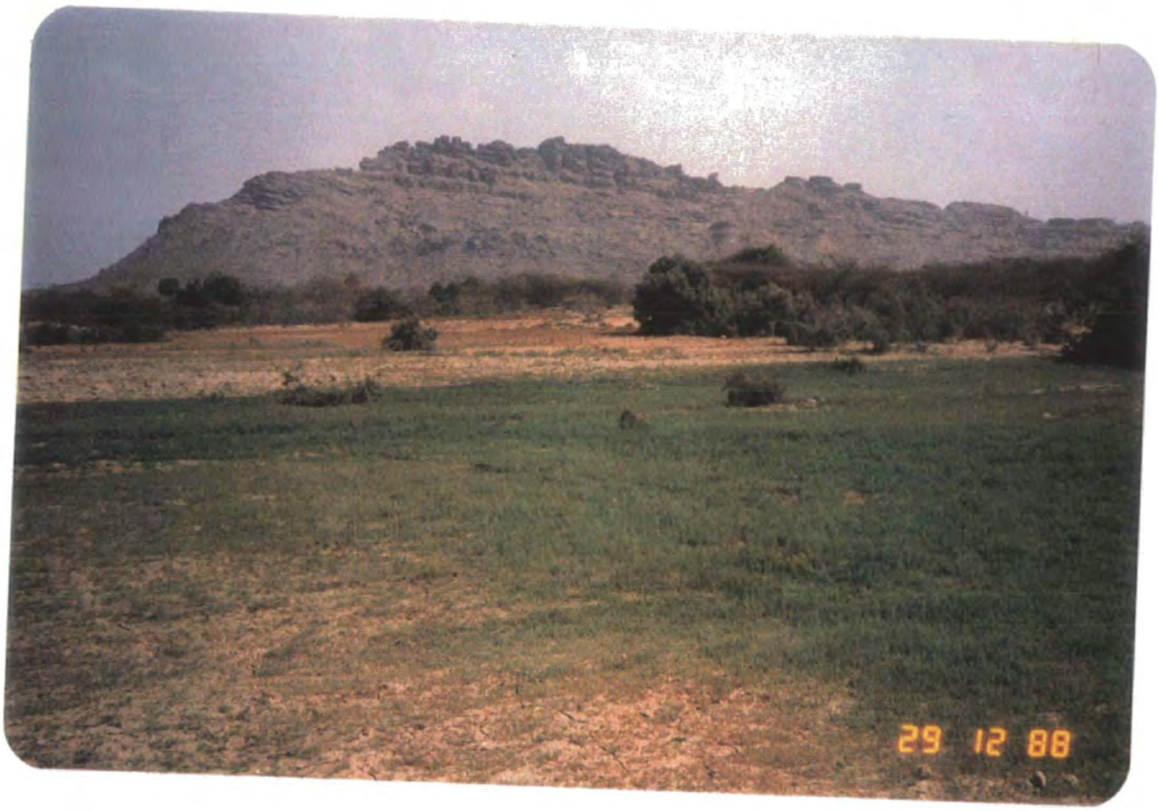
Figure 3.18

Down Wadi Jizan water flow in Wadi,

Figure 3.19
The Wadi Kohdirah uper ~~near~~ Wadi Jizan, there ~~some~~ water stay after rinfall in Tihama Asir

Figure 3.20

Vegetation after rainfall at Wadi Khodirah upper Wadi Jizan in Tihama Asir



ensure an annual supply of water to at least 6,000 ha of spate irrigation and irrigation from groundwater for initially 1,000 ha.

Considerable surface remnants of this main terrace are preserved in the widened valley of Wadi Jizan and its many branches above the narrow passage at Malaki.

Wadi Jizan is cut into this middle terrace in the form of a 5 to 10 km wide bed, the floor of which consists mainly of fine sandy to silty drainage, 0.5 to 1.5 m deep, which diverge sharply and gradually disappear on their way to the coast.

Annual water flow in the wadi is 80 mcm, and the frequency of runoff in the wadi varies from 15 to 35 times per year, each one runoff measuring between 0.5 and 10 mcm.

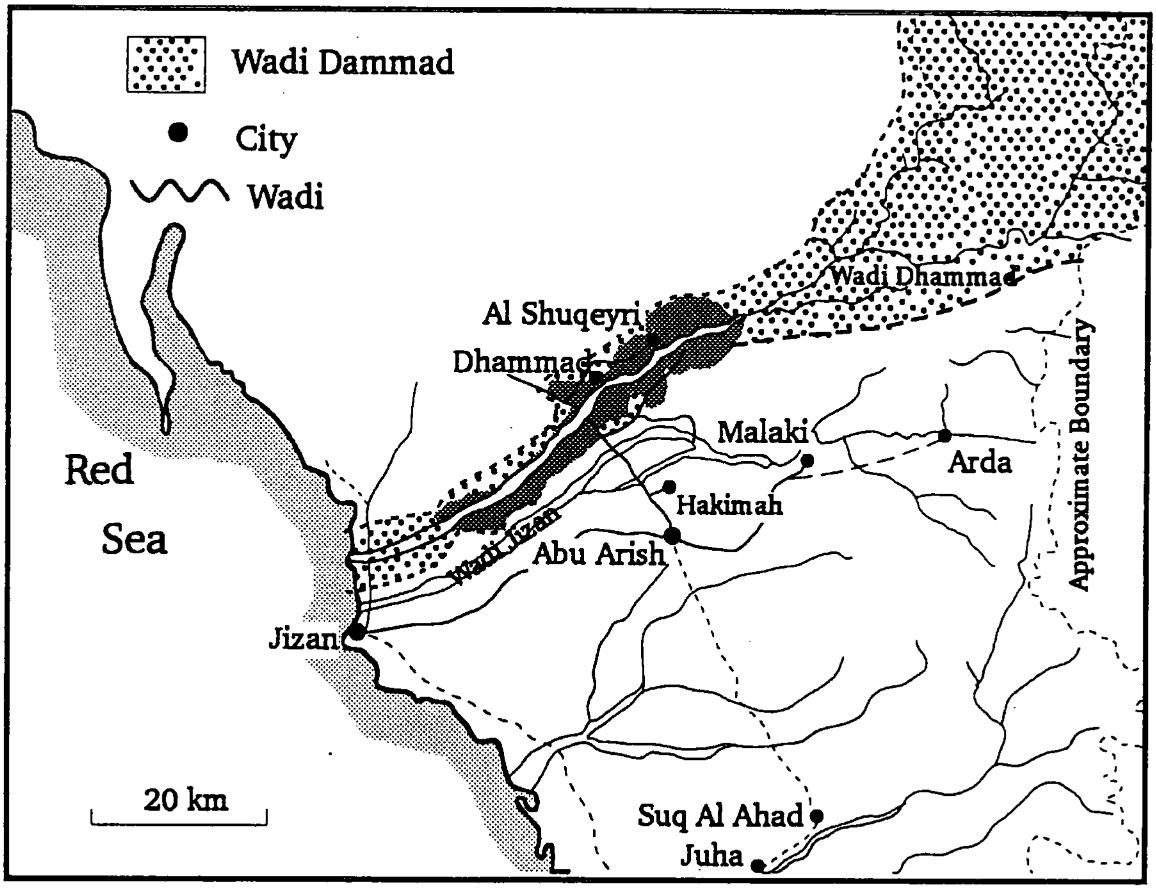
E. Wadi Dammad

Spate irrigation of agricultural lands by use of aqms (low earth embankments which are constructed in order to divert the path of a flood so that it will irrigate the land, but which tend to get washed away in major floods) in Tihama Asir, including Wadi Dammad, has been carried out for centuries.

Wadi Dammad is one of the most important wadis adjacent to Wadi Jizan with similar soil and flood characteristics and where spate irrigation with earth embankments is traditionally used for seasonal irrigation. Figure 3.21 shows the Wadi Dammad area with another wadi in Tihama Asir, and an irrigation development project.

Wadi Dammad lies on the heavily faulted western edge of the Asir Mountains. The catchment area consists of an upland region of mainly Precambrian schists and an alluvial plain region of mainly Quaternary age bordering the Red Sea. The two regions are separated by an extensively faulted zone between 5 and 10 km wide, characterised

Fig. 3.21. Wadi Dammad



by outcrops of volcanic and intrusive rocks and minor sedimentary units of mainly Tertiary age (see chapter 2).

Wadi Dammad plain lies in a hot arid climate area which is sometimes moderated by monsoons from the Arabian Sea. It experiences very high temperatures, exceeding 40°C in May-July and temperatures as low as 12°C in December-January.

Wadi Dammad rises in the Asir Mountains and crosses South Tihama to discharge its water in the Red Sea. The catchment area is about 1084 km^2 and some 2000 m above sea level.

The soils of Wadi Dammad are similar to those of Wadi Jizan. They are sandy and fine sediments deposited by many years of floods, making deep soils with high capacity for water retention.

The system of water allocation is laid down by local customary law which is acceptable to all farmers. Water is diverted out of the wadi bed by sand embankments called aqms and then passed from field to field. Each aqm serves well defined areas of water rights in sequence, to allow water to pass down to the next aqm, until all the fields are irrigated with the water available.

Wadi Dammad is one of the important cultivable areas in southern Tihama where studies were carried out for the improvement of distribution of flood water and exploitation of ground water by tube wells to contribute to increased agricultural productivity. The objective of the development of Wadi Dammad is to improve the present traditional irrigation from surface water and the utilisation of ground water for perennial irrigation (MAW).

Groundwater resources are estimated at 10.3mcm/year for Wadi Dammad and 25.8 mcm for Wadi Jizan. The annual available groundwater for both wadis is 27 mcm and is in general suitable for irrigated agriculture and domestic uses (Noury, 1984). Table

3.6 gives the discharge water in Wadi Dammad 1978-1991. Total discharge varies from year to year, as does peak flow. An experimental extension of records for the wadi compared to the recorded flows suggests different peak runoffs for rainfall coming from the Asir Mountains. Perennial irrigation is based on a unit area of 25 ha supplied by one well. Annual water flow of the catchment area is 59 mcm and the medium annual flow available is 50 mcm. When the rainfall is heavy, peak flow is higher, e.g 4,000 m^3/s, compared with 175m^3/s when rainfall is lower. The average runoff, based on measured runoff in the gauged catchment, is 6% for wadis in the mountain, and 12% for wadis in the alluvial catchment. The period (of flood records) mean runoff for wadis in the eastern mountain. The extreme variability in runoff from year to year can clearly be seen in Table 3.6, which gives annual runoff totals for the catchment, and also the median annual runoff for the period of flood (peak) record.

3.5 Flood Control

A stream generally flows within the banks of its regular channel. Occasionally, during storms, the water rises towards the top of the bank. During heavier storms, in places where runoff is more frequent than elsewhere, and where the channel is just able to contain regular runoff, the water may breach the wadi banks and spill onto the flood plain.

Peak flows generated during the night are very common, due to the heating of land surface which causes convective storms to develop at the end of the rainfall. These convective storms usually produce high intensity rainfall which causes sharp rises in wadi flow. The peak flow generated by a high intensity rainfall usually develops within a matter of minutes from the start of the rise in flow. Therefore, peaks, which have a tendency to overrun each other, produce hydrographs which have a configuration made up of a successive ascent of waveform-like rises. This is common in many wadis in Saudi Arabia, particularly in the Asir region.

Table 3.6: Discharge in Wadi Damad Between 1978 - 1991 mcm/y
Latitude 17° 09'; Longitude 42° 53'
(Drainage Area 1000 km^2; Altitude 130 m).

No.	Altitude 130 m											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1978[1]	10.706	0.628	0.000	0.738	14.168	1.595	26.489	44.290	25.569	3.160	0.107	0.082
1979[2]	0.208	2.290	137.850	13.120	65.390	6.000	34.600	58.610	38.145	12.200	3.440	7.780
1980[3]	7.760	7.860	61.260	194.985	14.530	64.912	175.230	321.070	96.542	4.087	0.923	0.599
1981[4]	0.922	13.313	18.677	30.817	4.484	146.893	69.860	137.170	136.710	40.736	61.962	22.029
1982[5]	7.183	0.627	12.351	55.765	165.256	2.335	15.670	76.670	115.290	75.090	46.430	33.430
1983[6]	46.148	60.400	1.812	21.624	31.840	1.336	372.495	13.680	13.348	24.223	60.441	0.304
1984[7]	105.130	4.300	22.790	2.340	30.040	1.580	4.690	56.870	5.290	9.270	3.430	33.330
1985[8]	0.480	0.290	3.580	1.840	3.560	2.460	16.140	132.210	25.380	18.100	0.340	3.450
1986[9]	2.530	1.630	141.700	147.270	21.360	8.280	43.360	54.760	78.090	52.280	26.930	19.280
1987[10]	49.520	78.730	78.340	105.200	65.930	27.890	69.340	70.410	72.990	40.740	18.230	97.620
1988[11]	51.830	27.700	90.050	90.190	97.050	25.490	29.720	42.140	12.010	9.530	12.100	4.410
1989[12]	11.237	1.268	0.000	6.337	0.000	7.097	23.348	16.266	1.176	1.378	6.012	19.240
1990[13]	31.414	0.728	23.591	385.240	49.675	0.000	1.080	13.692	37.005	10.270	13.470	7.130
1991[14]	9.010	9.690	8.875	189.835	5.160	0.798	11.648	87.961	47.864	32.403	20.536	23.238

Peak Flow of the Year was: (1) 860 cms on July 19; (2) 310 cms on Mar. 25; (3) 1520 cms on Aug. 12; (4) 390 cms on Sep. 8; (5) 510 cms on May 23; (6) 1180 cms on July 11; (7) 310 cms on Jan. 29; (8) 316 cms on Aug. 13; (9) 767 cms on Mar. 16; (10) 296 cms on July 18; (11) 265 cms on Apr. 18; (12) 175 cms on Dec. 10; (13) 4000 cms on Apr. 23; (14) Not calculated.

Peak flow can be reduced either by temporarily storing a portion of the surface runoff until after the crest of the flood has passed or reducing the amount of surface runoff through a change in land use which increases the infiltration capacity.

Reduction by storage is accomplished in two ways, by a large number of small, individual farm reservoirs located in the headwaters of the mainstream that they detain the surface runoff long enough to permit it to infiltrate into the soil, and by large dams located in the wadis further downstream.

For structural design purposes, surface water may be measured hydraulically or determined hydrologically, and offers a combination of climate (heavy rainfall), soil and available water for domestic and agricultural irrigation use. The height of the flood is of interest to those planning to build structures above or across streams. The height of a flood may be measured at point, as at a gauge in a fixed location, or in a reach, as is defined by a profile along both banks. Many roads, farms and villages are built across wadi plains on low embankments that will be overtopped by the higher floods (the floods in 1982 damaged the roads, farms and villages in Tihama Asir).

Every dam must be provided with adequate overflow arrangements. An earth or rock filled dam must not be overtopped by water or it would fail completely in a few hours, nor must overtopping of a concrete dam occur except when the design specifically provides for this. Various overflow devices are used and these can be classified into two distinct kinds, overflows which permit water to flow over the dam, and overflows which are driven through the abutment or through an open channel constructed in the ground.

The draining of wadis is probably the most important aspect from a surface hydrology point of view. Rainfall in the mountains and escarpment regions normally exceeds 300 mm/annum, The comparatively high rainfall, coupled with relatively impervious underlying geological formations and steep gradients provides for considerable volumes of direct surface run-off. Some perennial streams occur in the high regions and floods reaching the lower regions can be of major proportions and of greater frequency than others in Saudi Arabia.

3.6 Types of Dams

Due to the fact that rainfall is very limited and highly variable in Saudi Arabia, as it is in all arid areas, when flash floods occur valuable water is usually lost in the desert or by evaporation. This fact indicates the necessary and important role of constructing more dams in order to achieve maximum utilisation of this source of water. The main purpose of these dams is to collect the water from flash flooding; to prevent the flooding of wadis, oases, and villages; to recharge the depleted aquifers; and to irrigate agricultural land near the dam sites.

The geology of a wadi and the available supplies of suitable construction material will influence the location of a dam site and the type of dam that is constructed. Beneath every dam is built a cutoff. This is a thin barrier that extends into the foundation and either prevents or reduces the leakage of reservoir water under the dam.

The wadi rises from the mountains with different elevations. The catchment basin, which is sub-tended by areas such as Nammar and Malaki, at an elevation of between 135-300m, covers an area of between some 1,100-5,000km^2. Surveyors in the wadi found the area, built the dam, well suited for the reservoir site of the dam. Based on hydrological information of the area it was discovered that flow was good, and also that although the flood flows are most frequent between month to month. Hydrological data such as this was essential to the decision to construct the dam. A geological survey was also conducted in the area, focusing on the formation of the reservoir basin as well as the dam site. Choosing the type of dam to be constructed was based on geological, morphological and hydrological set-up of the dam is summarised as follows:

1. Catchment area of the dam site; and
2. river bed elevation; and
3. maximum discharge; and
4. minimum discharge; and
5. average annual flow with % frequency.

A number of different types of recharge dams are used in KSA: sandy, rockfill and concrete.

(a) Wadi Haneifa Dam is built of sand from a location in Riyadh.

(b) Thurat Qubaideh dam is built of rockfill from a district located in Asir.

The water controlled by dams can be stored either on the surface or underground by using deep cut-offs made of plastic slurry 40 to 80 centimetres wide, the most common width being 60 centimetres (Al- Hajeri and A. Sheikh, 1982) (see Figure 3.23). The underground storage method, currently being used in many areas of the world, is preferable to surface storage because of its ability to minimise evaporation and pollution. This method also has the ability to replenish the depleted aquifers, thus preventing soil and nearby sea water from intruding into the empty spaces in the aquifers.

Dams vary in length from 2.6 m to 1260 m and in height from 5 m to 60m. Their storage capacity varies from 40 mcm to 85 mcm (Table 3.6). More than 200 dams have been built, which is of great benefit in water storage and controlling flood water, and is useful for agricultural purposes, irrigation and domestic use. The Table lists the location of smaller dams which have been built in Saudi Arabia. They have various lengths and heights, and also different storage capacities for different purposes. Their most important function is to improve the recharge ratio and therefore the water yield

Figure 3.22
The Earth Dam under construction Northeast of Dhruma

ratio, by capturing surface runoff and thereby increasing percolation to recharge shallow aquifers. Most of these ancient dams are built of sand, rockfill and concrete, are 5 to 10 m in height and are 100 to 200 m in length. Figure 3.22 shows a new 3.5 km earth dam under construction north of Dhruma, near the base of the Tuwayq escarpment. The main function of the dam is groundwater recharge.

Table 3.7: *Location of Dams and Reservoirs in Saudi Arabia*

Name of Dam	District Location	Type of material used	Length (m)	Height (m)	Storage capacity cu.m.
Hancifa	Riyadh	Sandy	390	9.5	1,300,000
Laban	Riyadh	Rockfill	500	12	2,000,000
Nammar	Riyadh	Rockfill	400	8	1,500,000
Dir'iyah	Al Duriyah	Concrete	300	9.5	3,000,000
Ha'ar	Riyadh	Concrete	400	14	3,800,000
Safar	Riyadh	Sandy	325	5	300,000
Gobera	Riyadh	Sandy	170	6	90,000
Harcka	Riyadh	Sandy	190	6	80,000
Galagel	Sudia	Sandy	630	11.6	1,750,000
Melham	Sudia	Sandy	100	5	200,000
Herimlah	Sudia	Sandy	1250	6	1,500,000
Majma'a	Sudia	Rockfill	360	8	1,300,000
Thadek	Sudia	Sandy	850	7	2,000,000
Rawdat Sudair	Sudia	Sandy	554	14	3,000,000
Alghat	Sudia	Sandy	250	11	1,000,000
Al Khalah	Al Baha	Concrete	60	7	200,000
Jizan	Jizan	Concrete	316	35	51,000,000
Saab	Al Tarif	Sandy	290	10	500,000
Abha	Asir	Concrete	350	33	2,400,000
Bathan	Medina	Concrete	26	12	500,000
Akramah	Taif	Rockfill	300	8	400,000
Shakrah	Shakrah	Rockfill	90	10	200,000
Marid	Al-Asyah	Sandy	500	7	1,300,000
Ukdah	Hail	Sandy	100	7	100,000
Assalf	Hail	Sandy	230	6	150,000
Rabigh	Rabigh	Sandy	800	6	diversion weirs
Merrat	Merrat	Sandy	110	12	40,000
El Turah	Medina	Sandy	450	15	2,000,000
Al Kammah	Qassim	Concrete	700	7	1,500,000
El Ghab	Medina	Sandy	650	11	1,000,000
Hajlab	Asir	Rockfill	110	12	1,000,000
Al Safrat	Sudain	Rockfill	490	13	1,000,000
Saroom	Asir	Concrete	75	13	1,000,000
Najran	Najran	Concrete	250	60	85,000,000
Al Shara'a	Dowadune	Concrete	95	11	1,000,000
Lyyah	Taif	Rockfill	190	45	10,000,000
Turabath	Taif	Concrete	380	21	20,000,000
El Hamabig	Dowadme	Sandy	700	7	3,500,000
Sdoos	Salloukh	Sandy	520	7	700,000
Al'arkai	Medina	Concrete	450	11	7,000,000
Hawtat Bain Tamim	Hawtat Bain Tamim	Sandy	770	13	3,500,000
Semon	Zulufi	Rockfill	150	21	1,500,000
El Geel	Al Aflaj	Concrete	126	11.5	2,500,000
El Sharabil	Medina	Sandy	500	8.5	88,000
Thama	Belkan	Concrete	145	15	325,000
Thurat Qubaideh	Asir	Rockfill	170	22	1,500,000

The main objectives of the dams are to provide flood protection to land and properties downstream of the dam, and increase water supplies for irrigation. Figure 3.23 shows Al-Duriyah Dam near Riyadh. The dam was constructed to contain runoff for recharge into the alluvial aquifer. The dam is designed to store 86 million cubic metres (mcm) at spillway level and to pass a peak discharge of 8700 m^3/s. Outlet pipes will be installed to release water to replenish the groundwater downstream of the dam. The construction contract includes considerable streambank stabilisation, work intended to protect from damage low-lying land along the wadi. The specific details of this dam are:

Reservoir length at maximum water level	9 km
Length of spillway	75 m
Total excavated earth and rock	225,000 m^3
Total concrete	126,000 m^3

The Ministry of Agriculture and Water (MAW) has embarked on an ambitious conservation and dam construction project in Hijaz, Asir and Najed. Between 170 to 200 dams have been built to store run-off water to use for irrigation.

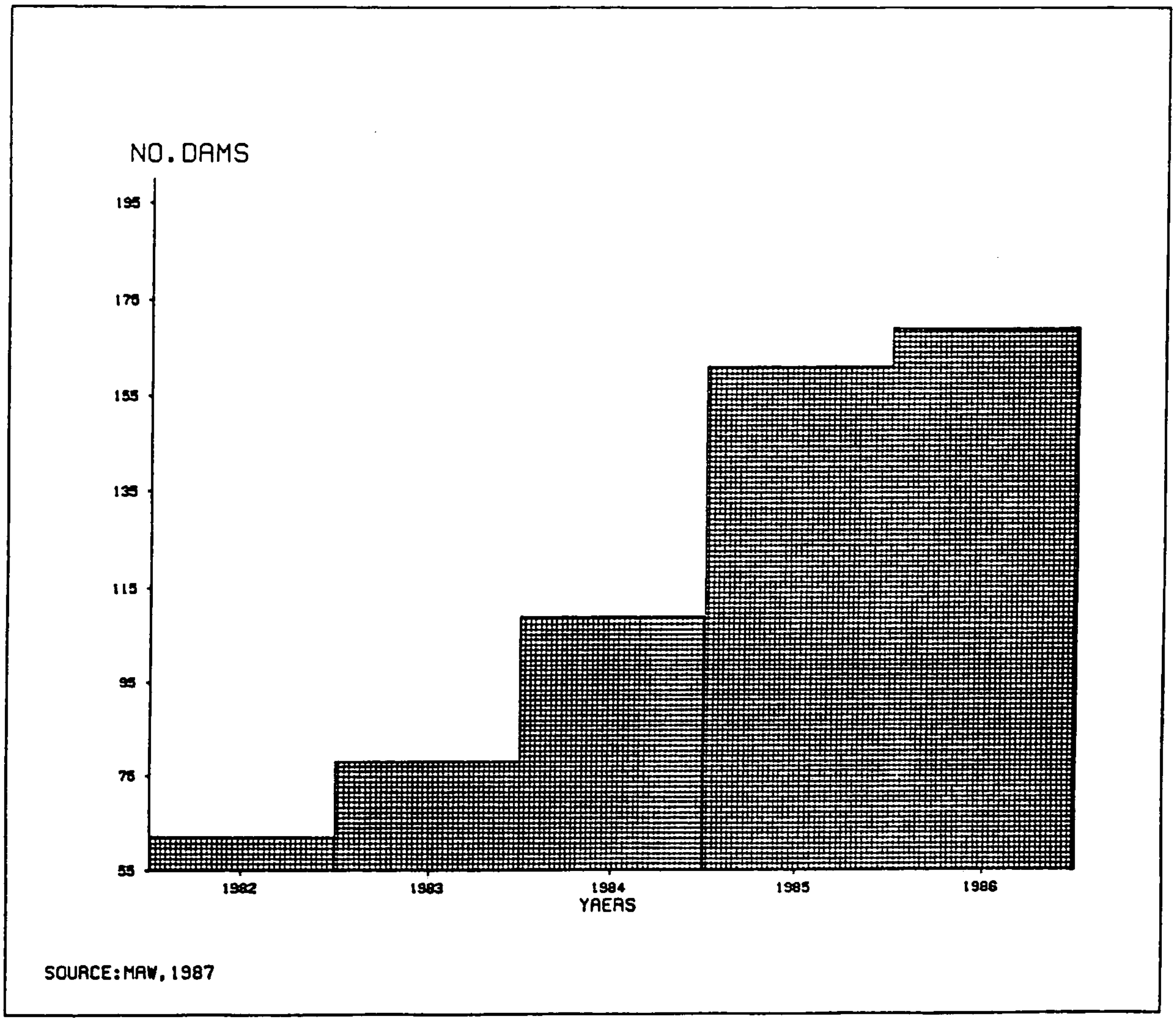
Table 3.8 and Figure 3.24 show the sites of dams and a number of reservoirs in KSA. The table gives, by year of construction for dams built between 1983 and 1987, the number of dams built for different purposes, and their storage capacity. The total of number of dams was 172, and their combined storage capacity is 413,149 mcm. Their use is for domestic water storage (53 dams), for flood control (35 dams), and aquifer recharge. Figure 3.25 gives the total number of dams built in Saudi Arabia during the period 1982-87. In 1982-83, nearly 78 dams were built for various purposes, and between 1984-86, nearly 169 were built but in 1987 it was found that the number built increased to 1972 dams to control flood water, for irrigation water use, for recharge water to underground and domestic water uses. A number of dams which are still

Figure 3.2 3.

Al-Duriyah Dam near Riyadh for underground recharge and irrigation

Figure 3.24

Total Number of Dams built by MAW between 1982-1986



under construction are intended to retain sudden floods and prevent them from inundating wadis, oases and villages; to increase the infiltration of shallow aquifers; and where appropriate to irrigate agricultural lands below the dams sites. Many of these dams are made of grouted concrete and have drainage channels and serves two purposes, flood control and the regulation of flow of water to the layers of water carrying soil thus raising the general outflow and supplying all the wells drilled along the general outflow and supplying all the wells drilled along the path of the reservoir thus increasing agricultural production and regulating it in an organised manner. They range in height, which is partly dependent on the underlying rock formation (see Chapter 2).

Table 3.8: *Number of Dams Constructed by MAW between 1983-1989*

Years	1407 (1987)		1406 (1986)		1405 (1985)		1404 (1984)		1403 (1983)	
Purpose	**Storage Cap.**	**No.**	**Storage Cap.**	**No.**	**Storage Cap.**	**No.**	**Storage Cap.**	**No.**	**Storage Cap.**	**No.**
Control	153586	45	153586	45	154036	45	142725	29	142325	24
Irrigation	51000	1	51000	1	51000	1	51000	1	51000	1
Compensation	157494	109	156970	106	129750	98	85531	72	75465	49
Drinking	48389	13	48389	13	48389	13	44930	3	2130	1
Protection	2680	4	2680	4	2670	4	2670	4	370	3
Total	412149	172	412625	169	385845	161	326856	109	217290	78
Storage Capacity (1000 Cubic Metres)										

Source: Project Execution Department

These dams are built first and foremost to save large quantities of seasonal rainwater by retaining it underground; to prevent sudden floods from inundating wadis, oases and villages; and where appropriate to irrigate agricultural lands below the dam sites so that it may be drawn as the need arises, either for the expansion of the cultivated area or for supplying the inhabitants with drinking water. The largest of these structures constructed so far is in the Wadi Jizan Dam. All in all, the dams built developments such as in Table 3.7 constitute a comparatively inexpensive but extremely worthwhile area of water resource development. As will be discussed further on, more attention and expenditure is required on these projects than on huge capital intensive programmes since in the long term they offer a more viable solution to water resources problems and agriculture water problems.

Every dam must be protected against sudden influxes of flood water into its reservoir by an overflow structure, such as a spillway or other outlet that discharges downstream of the dam. To construct a dam it is necessary to divert the existing surface water and its flood waters either by retaining it to the side of the wadi or diverting it into a tunnel that passes through the abutments and discharges downstream of the dam site. The geology of sites for appurtenances such as overflow structures and stream diversion works must be considered. Figure 3.25 shows the Bar Dam at Jabal Aja near Ha'il in the north of Saudi Arabia which is used to store water and recharge the alluvial aquifer.

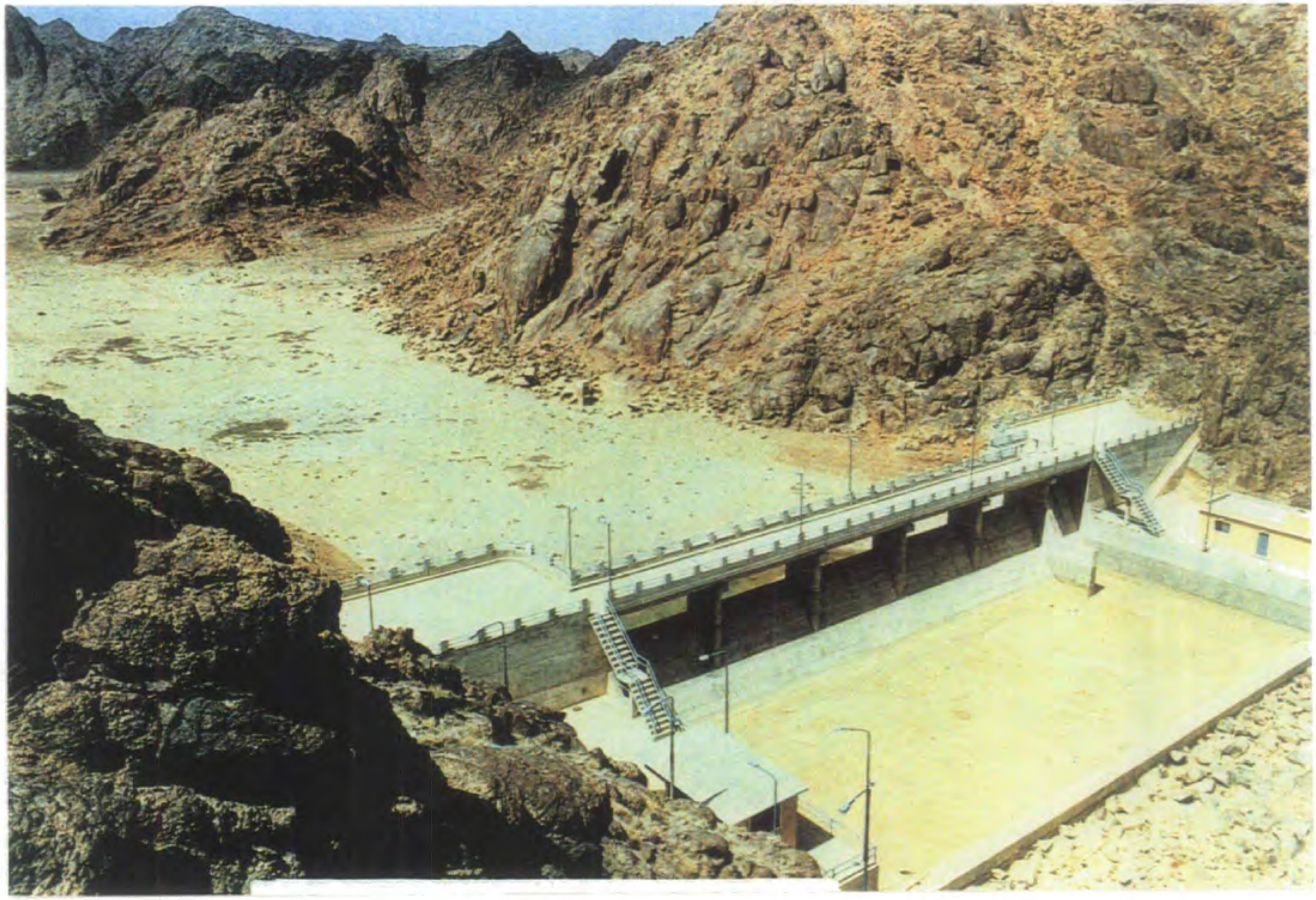
Subaerial erosion transports debris into wadi channels where it is carried as alluvium to lakes and the sea. A dam interrupts this natural sequence of events by preventing alluvium from travelling downstream. Sediment therefore accumulates behind the dam and reduces the volume available for the storage of water.

Sediment will also accumulate as deltas at the margins of a reservoir where wadis discharge into the lake. Around the lake a shoreline develops from the action of waves, generated by wind blowing across the lake.

In recent years the government, though its Directorate General of Water Resources, has carried out surveys of the country. A dam and irrigation section has been established to investigate and utilise both the underground and surface water potential. Many sites of ancient dams in Asir, Hijaz and Najed have been investigated for reclamation possibilities.

Figure 3.25

Bar Dam Jabal Aja near Hail used to store and recharge water



Agricultural irrigation has been, and despite rapid industrialisation and urbanisation and will continue to be, by far the largest user of water. Scarcity of water has been a major hindrance to the development of agriculture. In recent years, however, major agricultural schemes have been completed, such as the Abha, Jizan and Najran Dams. These dams are used for water storage, as well as providing potable water and water for irrigation.

Despite the construction of many dams in different parts of Saudi Arabia, vast amounts of water still flow and disappear into the dry alluvium wadis. Therefore, many wadis throughout Saudi Arabia would benefit from the construction of dams, particularly in the southwestern region along the Red Sea. The average rainfall there is higher than in the rest of the country and reaches 600mm in the Jabal Feifa area (see chapter 2, Climate). A tremendous volume of usable water is being discharged every year into the Red Sea or lost in the desert. It is estimated that the flood water is 1.265 mcm every year and the used portion of it is estimated to be less than 20% of the total volume (A. Bushnak 1982). Therefore, constructing more dams in the part of the country to capture this vast amount of water would have an important impact on the country's water supplies. In addition, many inland wadis need dams to retain this precious source of water.

The MAW, since establishment, has continued to construct dams. Therefore between 178 to 200 dams of different volumes and types, and different purposes have been constructed in KSA. The dams operation record including the water level movement in the reservoir to date is therefore valuable showing clearly a hydrological behaviour of the dams.

Each wadi's dam has different characteristics with the purpose for type of dam building, such as Wadi Jizan Dam, Mudhiq Dam in Najran, Wadi Abha Dam, Majma'a Dam, and Bathan Dam, the dam is located at the area boundary of a city, a village and farm, tapping water from the wadis at its uppermost basin, Some 30% of the catchment area is terraced farms and the other areas are mostly forest but rocky. New roads and residences are developing into the area.

1. Bathan Dam

Medina City suffers from floods coming from the south east. The largest flood, in 1963, caused great loss to houses and other properties. Following these floods, possibilities of protecting the city from inundation were studied. As a result of studying different wadis a dam site was selected 6 km from Medina City at Wadi Batham, the largest wadi in the south east carrying floods to the city. Rainfall in the area is rare, and the reservoir water is used for domestic and agricultural purposes as well as groundwater recharge.

The wadi split at the dam site into two arms separated by a small basalt hill. The dam was constructed either side of the hill. The main part of the right wing comprises a concrete structure core in the middle. The left wing of the dam is similar and supported by pillars at 3 m intervals with a 4 m wide passageway over the dam. The dam is 266 m in length and 12 m in height. The amount of water available, the results show that even for a conservative consumption of 0.62mcm/y or 1,700m^3/d. There is a period of 6.4 months of completely dry reservoir out of consecutive six years. The foundations are of concrete slab from 1.25-35 m thick grouted underneath and in three rows to a depth of 10 m. The resulting storage capacity is 80,000 m^3.

The characteristics of the dam are as follows:

Length of the main right wing	108 m
Length of the main left wing	90 m
Length of the main earth wing	98 m
Length of the main top width	4.5 m
Length of the main bottom width	9.25 m
Height of concrete structure	12.1 m
Height of earth dam structure	11.5 m
Outlets	5, discharge of each: 12.5 m^3/s
Length of spillway	50 m
Storage capacity	80,000 m^3

2. Majma'a Dam

This dam is located at the junction of Wadi Mashghar and Wadi Ougheik about 7 km southeast of Majma'a village. Its construction was ordered by the government to limit flood damage to roads, farms and houses during the heavy winter rains, and also for groundwater recharge and storage. The study included the hydrology of the catchments area, the geology and topography of the dam site, the silt deposits, and the storage capacity.

The dam is a compacted earth structure, with a top pavement 360 m long, and 11 m high, and with a concrete spillway 50 m long and 9 m high. The dam has an outlet on the left bank to release water for irrigation. The side slopes of the dam are covered with concrete paving on both upstream and downstream sides. The reservoir holds 1.3 mcm.

The characteristics of the dam are as follows:

Catchment	1460 km
Total length	500 m
Total height	36 m
Height of stored water	15 m
Maximum storage capacity	20 mcm
Top width	5 m
Bottom width	23 m
Length of spillway	380 m
Total excavation	10 mcm
Height of concrete structure	26 mcm

3. Wadi Abha Dam

Wadi Abha slopes down from the high mountains at Asir through rocky areas with steep slopes west of Abha City and a debouche in Wadi Bishah north west of Khamis Mushayt City.

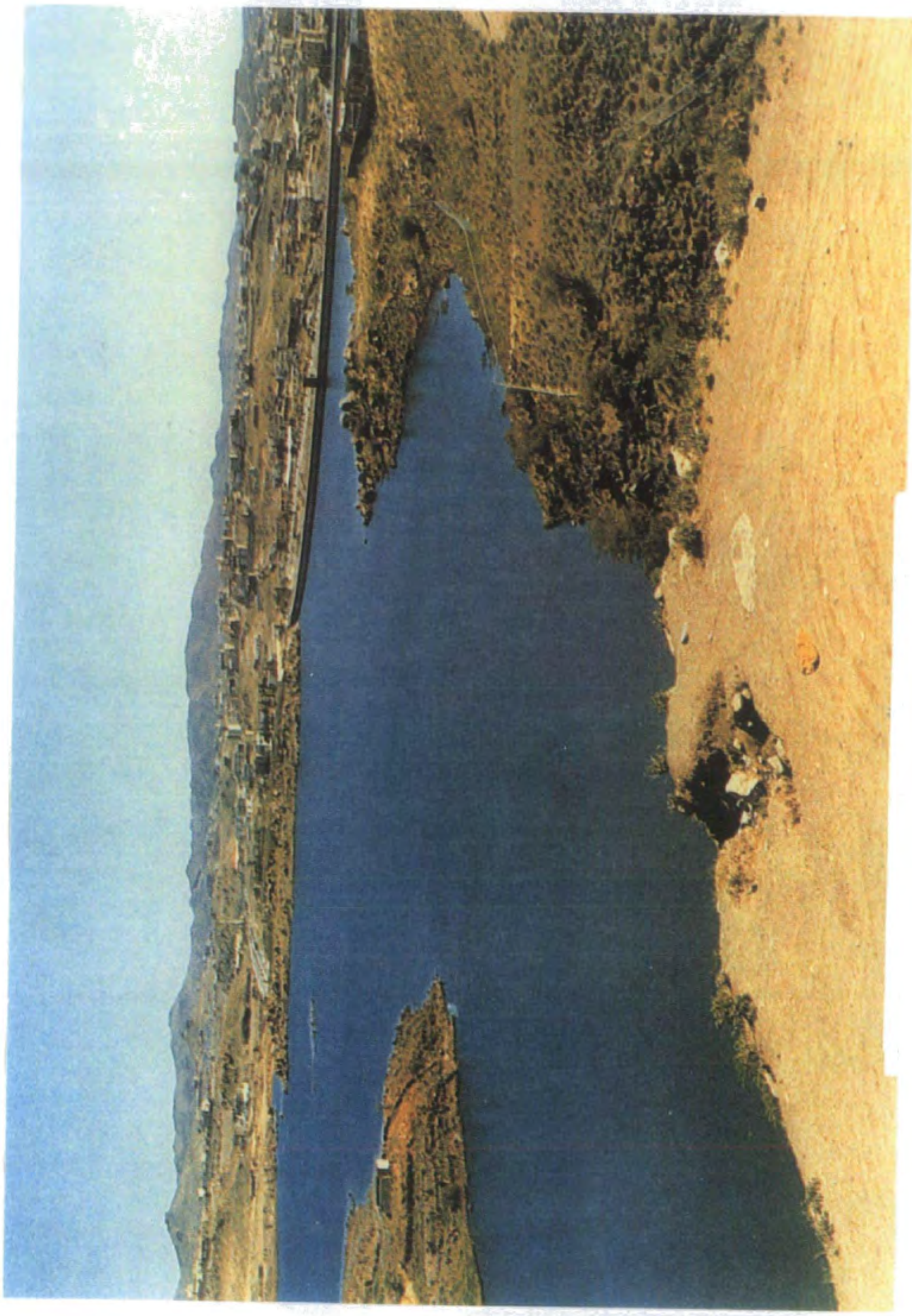
The catchment area of the dam is some 58.5 km^2 and lies in a zone of transition between summer and winter rainfall. At Abha Station there are three peaks of rainfall, in January, April and July- August. These run-off slopes are far from the lower reaches of the wadi at Abha.

The largest part of the catchment area is terraced or under forest. Thus run-off is slowed down and prevented from reaching the wadi bottom, except when the intensity and duration of the precipitation exceeds the rate of infiltration. Figure 3.27 shows the Lake Abha Dam and a view of Abha City. This dam is used for controlling flood water and to recharge the aquifer.

Abha City is located on Wadi Abha in an area of moderate climate and relatively cultivable lands. With a growing population, water from shallow wells became insuf-

Figure 3.26:

Lake behind Abha Dam, with view of Abha City



ficient for domestic use. There was therefore an urgent need to construct a storage dam to replace the old one with a storage capacity of 2.4 mcm. The dam structure is of solid concrete, with the following characteristics:

Total length	350 m
Top width	3.15 m
Bottom width	22 m
Height	33 m
Maximum storage depth	22.5 m
Reservoir area	286,000 m^2
Total storage capacity	2.4 mcm
Length of side spillway	38 m

4. Wadi Liyyah Dam - Taif

Liyyah Dam is situated at the confluence of Wadi Liyyah and Wadi Ardah about 8 km south east of Taif City at an elevation of about 2000 m above sea level. The catchment of both wadis is about 178 km^2. The average rainfall of the catchment area is about 300-400 mm/y, and the average runoff is about 2.2 mcm/y.

The main objectives of the dam are to provide flood protection, storage and groundwater recharge.

This rock fill type dam has the following characteristics:

Total length	190 m
Total Height	42 m
Total top width	8 m
Bottom width	140 m
Maximum storage capacity	10,000,000 m^3
Length of spillway	115 m
Total excavation	216,500 m^3
Total rock fill	225,000 m^3
Total concrete	2,700 m^3
Total length of grouting	2,400 m

The width of the wadi reservoir varies from 30 m to 50 m. The structure is of rockfill 90 m long and 42 m high, 8 m top width and 140 m bottom width. The storage capacity is 1,000 mcm and the length of the spillway is 115 m.

5. Wadi Jizan Dam

Rainfall into Wadi Jizan Dam and its basin varies greatly from year to year. On average there are 13 rainy days on the plain each year, concentrated mainly in July-August. The mountains have 30-40 or more rainy days annually. The number of floods varies from 15 to 33 per year with a volume of 0.510 mcm per flood. The main floods of July-August are characterised by a rapid rise to a high peak flow for a short period followed by a rapidly decreasing flow until the wadi is dry again. The average surface flow is some 80 mcm per year, and the total groundwater is estimated at about 2,000 mcm charged by infiltration through the wadi bed. Figure 3.28 shows Jizan Dam which is built in the Jizan Wadi at Malaki, 35 km from Jizan City.

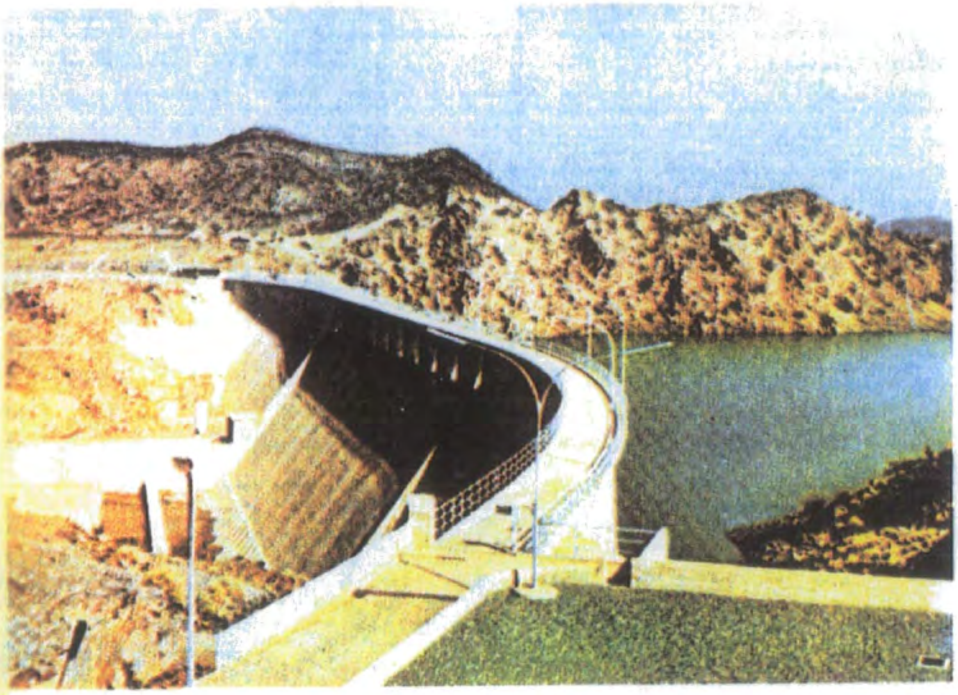
The hydrological regime at Wadi Jizan regarding the proposal to build the dam is as follows:

Catchment area at the dam site	1100 km^2
River bed elevation	130 m asl
Maximum discharge	2100 m^3/s
Minimum discharge	23 m^3/s
Average annual discharge with 80% frequency	83 m^3/s
200 year frequency	2850 m^3/s

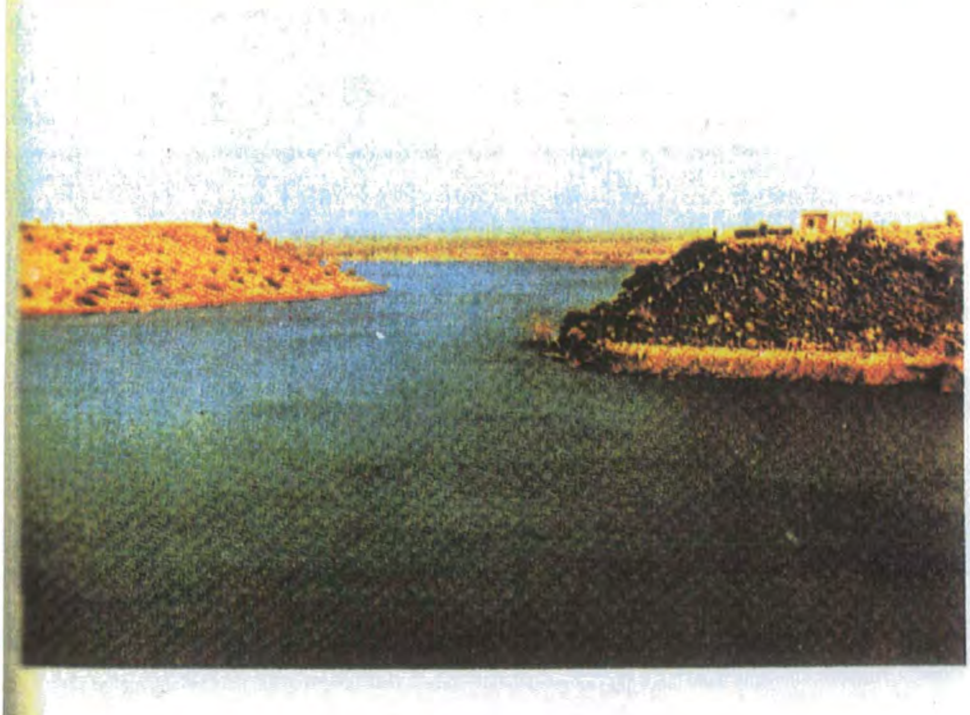
The Wadi Jizan Dam was constructed for two purposes:

1. To regulate the flow of Wadi Jizan and to protect the lands downstream from damage during the rainy season, as floodwater usually washes away many aqms, and sometimes uproots plants and washes away seed. It also carries away the

Figure 3.27: *View of Jizan Dam*



Jizan Dam



good alluvial soils and in many cases causes losses of livestock and destruction of houses.

2. To enable further expansion of the agricultural area through release of the stored water for control led irrigation in accordance with need and at the right time.

The catchment area upstream of the dam is about 1,100 km^2 with five wadi tributaries contributing flows, namely Wadi Misherf, Wadi Jizan, Wadi Haraba, Wadi Khashabat and Wadi Al-Barda. About two-thirds of this catchment area lies within the Yemen. The inflow into Wadi Jizan reservoir is the same and equal to the surface runoff generated from precipitation over the catchment area upstream of Wadi Jizan Dam.

It is in solid concrete with the following characteristics:

Total length	316 m
Total height	41.6 m
Top width	3.6 m
Bottom width	40 m
Height of spillway	5.44 m
Diameter of outlets (two)	1.7 m each
Earth and rock excavated	140,000 m^3
Total concrete	145,000 m^3
Total length of grouting	40,000 m^3
Maximum storage capacity	71 mcm
Water available for irrigation	51 mcm

The total cost of the dam was equivalent to US$8.4 million in addition to US$1,029,000 for the cost of studies and supervision of the construction. Over 700 labourers and 50 technicians worked on the construction.

6. Mudhiq Dam - Najran

MAW carried out a study for the Mudhiq Dam in 1977. It has a catchment area of about 4,520 km^2, with ground elevation ranging from 2900 m at the upper watershed to 1900 m at the Mudhiq site. Figure 3.29 show the Sadd Mudhiq which is located in a deep gorge about 500 m downstream from the confluence of the Wadi Marwan and Wadi Irdh near Najran. The reservoir area is in a sealed basin formed by jointed igneous and metamorphic rocks. The gorge is narrow with steep sides. The bow-shaped dam is 250m in length, 140m in radius, 60m high, and 9.5m thick. It is used for flood control, ground water recharge and to supply water for irrigation.

The structure is designed to store 86 mcm at spillway level and to pass a peak discharge of 8700 m/sec, with pipes installed to release water to replenish groundwater downstream of the dam. There has been considerable stream bank stabilisation work to protect low lying areas along the wadi from damage.

The characteristics of the dam are:

Reservoir length of maximum water level	9 km
Length of spillway	75 m
Total excavated earth and rock	225,000 m
Total concrete	126,000 m

7. Wadi Bishah Dam

Wadi Bishah Dam lies some 15 km upstream of Bishah City along Wadi Bishah, with a catchment area of 1800 km^2.

The wadi and its tributaries are in the Basement Complex of Precambrian age (see Chapter 2) which consists of chlorite schists diabase, and esite slate greenstone, intruded by granite and cut by dikes and rhyolite. The upper parts of the rocks are fractured and decomposed.

Figure 3.28: *Mudhig Dam in Najran built for the control of flood, ground recharge and water supply for irrigation*

The average rainfall of the catchment area ranges from 100mm to 400mm. The principal purposes of the dam are to provide flood protection, storage and groundwater recharge.

Dams which do not depend on carry-over storage for proper functioning include run-off from the wadi dam to create a head for power generation purposes, water diversion structures, debris dams, and dams to control water levels for other purposes. A dam on a stream channel changes the hydraulic characteristics of flow and sediment transport capacity.

Detailed studies for the dam were completed in early 1985 (1405h). The contract for construction was in 1987 (1407h). The dam is expected to be completed in 1994 (1414h). The dam's specifications are as follows:

Catchment	1800 km^2
Total length	507 m
Total height	113 m
Height of stored water	18 m
Maximum storage capacity	325 mcm
Top width	12 m
Bottom width	80 m
Length of spillway	500 m
Estimated excavation	1.5 mcm
Estimated concrete	1.3 mcm
Outlets	6

Figure 3.9 shows the approximate location of completed active dams under construction in 1981.

3.6.1 Conclusion

In order to describe fully the hydrological characteristics of a wadi system, and to correlate surface runoff with rainfall, it is necessary to measure the surface flow discharging into the wadis' reservoirs through the different tributaries, and its variation in time and space. This can be achieved initially by installing water levels meters, one just upstream of the dam site and the other at a reasonable control section on each of the wadis contributing (such as Wadi Jizan). Special recording systems have to be provided to work under wet and dry conditions as it is the case for these wadis.

With regard to the construction of recharge dams, such as Wadi Najran, it must be remembered that suitable dam sites are a finite resource. It seems that governments in the region are often referring to the need to construct recharge dams in order to retain storm runoff to recharge aquifers. However, such plans are often made without any consideration of precisely where such dams are to be built.

The wadis dam located at area, the purpose of such dams is to reatain sudden floods thereby preventing the inundation of cities, villages, and land, to provide a source of irrigation water, and perhaps to stabilise the present groundwater extraction recharge ratio by improving water yield ratios by capturing surface runoff thereby increasing percolation to recharge shallow aquifers. The dams operation records will play an important role in clarifying the rainfall-runoff system at the basin. That is what is attempted.

Intermittent surface water is primarily available in the southwestern highlands and coastal areas. Bodies of surface water from temporarily following heavy storms, except in the southwest highlands and some small eastern lakes in oases. Lakes and ponds formed by spring discharges are also present. Surface runoff depends on the effective rainfall and is proportional to its duration and intensity.

Runoff usually occurs in the dry wadis and often do not reach the sea becayse of high evaporation and high infiltration into the wadi alluvium, except in the Tihama Asir.

The main advantage realised from the dams thus far has been the decreased amount of damage to homes and land from flood waters, and preventing water loss to the desert or to the sea. As far as irrigation goes, an increase in the amount of irrigated land can be seen. For instance, from 30.5% of the irrigable lands, such as Wadi Jizan and Wadi Najran. Although the dam has improved the water scarcity problem somewhat, the expectations for the amount of cultivated lands and agricultural production have not been met. These factors which are hindering the meeting of such expectations. As the available surface water is dependent upon rainfall, it varies from year to year. Obviously, the dam is only responsible for storing water, not creating it.

3.7 Water Pollution

Surface waters, dam lakes and wells are specialised habitats of plants and animals, their ecosystems are particularly sensitive to changes induced by man in the water balance and in water chemistry. Not only does our industrial society make radical physical changes in water flow by construction of engineering works (dams, irrigation systems, canals, dredged channels) but we also pollute and contaminate our surface waters with a large variety of wastes.

The pollution problem is greatest in the lower portions of watershed/wadi basin ecosystems. The pollution may result from excess nutrient leaching from farm lands, and from industrial, human or livestock effluents. Increasingly cultivators are obliged through scarcity of uncontaminated supplies to use water that is heavily contaminated with organic pollutants, for example, sewage effluent or irrigation return flows.

Surface waters are not only complex physical, chemical and biological systems each within its own right, but they also display a wide variety of habitats: ponds, pools, lakes, impounded reservoirs, moving water streams and large wadis. A commercial detergent powder usually contains a surface-active agent of which the most common is alkylbenzene sulphonate together with sodium tripolyphosphate and tetrasodium pyrophosphate. This lathers well and simulates soap. Detergent factories and town effluents discharge large quantities of detergents into wadis. Alkylbenzene sulphonate is resistant to bacterial decomposition. All these aquatic ecosystems have ecotones with other terrestrial ecosystems having greater or lesser effects on them and being affected in a similar way. Many plants and animals have to be considered, together with an almost infinite variety of environmental conditions.

The forms of pollution listed below often also severely damage the aesthetic qualities of landscapes, of streams and lakes.

In urban and suburban areas pollutant matter entering streams and lakes includes deicing salt, law conditions and sewage effluent. In agricultural regions, important sources of pollutants are fertilisers and the body wastes of livestock. There is also thermal pollution resulting from the discharge of coolant water from electricity generating plants.

Water is used by man and returned more or less polluted and, therefore, not only is the integrity of the ecosystem threatened by the abiotic environmental modification but water quality and quantity are modified on a short, seasonal or longer term basis.

Sewage introduces live bacteria and viruses that are classed as biological pollutants. These pose health hazards to man and animals.

Waste water can be treated to remove physical, chemical and organic pollutants. Simple settling may be sufficient. A well-designed intake canal or system of silt traps can remove sufficient sediment and silt to avoid water supply system from choking up. It is usual to refer to the screening out or settling out of sediments as 'primary' or 'physical' treatment.

Chemical pollution by direct disposal into streams and lakes of wastes generated in industrial plants is a phenomenon well known to the general public and can be seen in any industrial community in the United States and UK. Direct outfall of sewage, whether raw or partially treated is another form of direct pollution of streams and lakes on which there is little need to elaborate, for it, too, is a commonplace phenomenon for all to see and smell. For example, in Germany, something fell by 8,000 micrograms/m^3, but nitrates rose 3,900 micrograms/m^3 in 1983. Phosphorus levels remained about the same, and values for cadmium, chromium, and copper decreased substantially.

In Saudi Arabia, the pollution significantly alters the quality of both surface and ground water, often creating critical health hazards. For the purpose of analysis and control, pollution may be divided into two major types, industrial and domestic. Of the two, industrial pollution, or waste, is the more dangerous because it may contain toxic chemicals. The east of the country has a lot of chemical factories, such as Al-Jubail City, it needs water supply to carry away all rubbish to throughout into wadi there, and discharge into groundwater aquifer.

At present, the volume of industrial waste in Saudi Arabia is low. Domestic waste, such as municipal sewage water, creates far more severe problems. In order to deal with them effectively, Saudi Arabia has established standards that regulate the quality of waste water that may be discharged into a wadi. These regulations aim to prevent the addition to the environment of polluted water which would create health problems downstream (such as north Al-Taif and Al-Hayer near Al- Riyadh), and groundwater (aquifer). That when leaf sewage flow from city to reach wadi around it, the water discharge into groundwater without infiltration.

The most significant hazard associated with the influx of sewage water into a wadi is the potential for pathogens to be present in the waste. This can occur if the waste treatment plant receives a greater volume of waste than it is able to cope with. Then the overflow becomes mixed with stream water, as in Taif, or recharges the groundwater. Domestic waste water, not least in Tihama Asir, is also likely to contain large amounts of nutrients that cause small plant and animal life in the wadi to flourish. This enriched condition can lead to unsightly appearance, foul odours, the growth of undesirable parasites and the deposition of bottom sediments.

Although, the industrial waste and domestic waste reuse would solve the problem of unregulated sewage which could pollute Saudi Arabia's environment. In addition, this unregulated sewage provides a breeding ground for a host of parasitic diseases.

3.8 Run-off in Tihama Asir

Although Tihama Asir constitutes less than 10% of Saudi Arabia, 60% of the country's runoff occurs in Tihama Asir. The mean annual rate of runoff in the Tihama Asir has been estimated as 39.8 m^3/sec. About 27 m^3/s of this runoff occurs in the northern area (MAW).

The inland surface runoff occurs where the highest rainfall occurs, meaning that the results of the relationship between the runoff, rainfall and the soil moisture, which represents the state of soil moisture in wadi watershed and is the main factor to produce or absorb runoff. The estimated average annual runoff from the whole begins in the region. For this attempt, an average annual rainfall has two seasons, one for the spring-summer rain type, the other for the winter rain type for area.

The relationships between rainfall and surface water in the Tihama Asir study have been defined for monthly, daily and annual values. These equations can easily be transformed to express the relationship between surface water and rainfall by the following facts:

The inflow into an area's reservoir is the same and equal to the surface water generated from precipitation over the basins.

The basin area upstream has an area of more than 3,300 square kilometres.

The coefficient of surface water is the ratio between the amount of rainfall, and the amount of discharge at a certain control point resulting from rainfall over the basin area upstream of the point. The coefficient of surface water change may be constant for many basins. The runoff of the wadis are shown in Tables 3.9 and 3.10 in which that the flood for the surface water will rise in volume more rapidly in wetter periods. Therefore, it is of great importance that cautionary and control measures are carried out for higher rainfall values than for lower rainfall values since the former may result in disastrous floods. During this period, the water level of the wadi rose, the records are in some hourly the peak flood period, clearly the rising flood in varying rates of the water level movement for a period. However, the water rising speed was recorded to be more than 50cm an hour for the flood peak in the wadis, and the peak floods are highest between 668 m^3/s and 6,000 m^3/s, indicating that rainfall is heavy rainfall and floods from the mountains are high. The relationships defined in this study are based on averaging the rainfall values at ten selected rainfall stations around the basin area due to the surface water of an efficient rainfall station network to cover the entire basin. This study has its discharge, and it is assumed that such an average would be more or less representative of the actual rainfall over the basins, as shown in the tables (also see Chapter 2 regarding climate in Tihama Asir).

Tables 3.9 and 3.10, and Figures 3.30 and 3.31 give the average monthly rainfall and run-off in Wadis Dogah and Hali. The figures compare monthly rainfall and run-off.

Table 3.9: Discharge in Wadi Hali Between 1978 - 1991 mcm/Y
Latitude 18° 46'; Longitude 41° 35'
(Drainage Area 4576 km^2; Altitude 298 m).

	Altitude 130 m											
No.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1978 (1)	81.980	9.080	0.728	11.537	128.620	10.627	1.381	164.980	136.190	36.170	95.370	246.370
1979 (2)	26.850	12.400	308.880	1.012	193.435	245.420	5.437	165.434	67.447	9.832	0.559	17.821
1980 (3)	5.000	11.100	25.870	531.330	0.880	6.930	27.940	206.410	142.470	30.270	3.540	39.110
1981 (4)	80.760	9.670	7.900	43.490	172.780	46.620	13.190	94.850	135.490	38.660	68.830	4.250
1982 (5)	127.320	37.370	4.710	11.800	92.830	26.460	24.430	114.91	31.900	172.400	51.250	92.660
1983 (6)	56.700	56.360	65.410	74.390	534.440	2.950	855.050	32.940	36.940	25.540	18.470	7.690
1984 (7)	60.210	8.540	7.510	9.800	39.170	46.400	26.460	271.190	233.310	113.420	114.010	33.400
1985 (8)	14.770	174.570	69.950	43.270	273.070	20.890	1.330	55.230	77.810	29.710	209.260	36.460
1986 (9)	3.080	3.020	56.170	9.760	35.560	4.990	11.470	56.000	36.910	30.570	1.030	0.000
1987 (10)	542.960	598.400	26.290	31.580	194.280	36.650	32.420	10.690	74.210	61.340	16.880	23.380
1988 (11)	24.890	607.590	14.830	14.000	18.990	12.570	9.869	27.336	11.406	0.000	0.000	19.990
1989 (12)	20.220	4.110	0.000	5.780	121.358	2.365	1.063	49.130	124.260	33.360	6.870	6.580
1990 (13)	6.650	2.470	0.232	261.850	565.450	63.400	26.380	83.290	313.300	47.690	272.600	95.480
1991 (14)	24.410	102.920	321.820	150.630	6.420	22.750	104.570	292.720	87.460	246.350	94.610	40.130

Peak Flow of this Year was: (1) 750 cms on Dec. 26; (2) 675 cms on Mar. 24; (3) 362 cms on Apr. 1; (4) 94.5 cms on Jan. 7; (5) 266 cms on Jan. 28; (6) 3320 cms on July 23; (7) 236 cms on Aug. 17; (8) 500 cms on Nov. 9; (9) 120 cms on Aug. 19; (10) 6000 cms on Feb. 13; (11) 1520 cms on Feb. 3; (12) 560 cms on Sep. 30; (13) 2280 cms on May 10; (14) Not calculated.

Table 3.10 Discharge in Wadi Dogah Between 1978–91 mcm/y
Latitude 19° 45'; Longitude 41° 02'
(Drainage Area 970 km²; Altitude 80 m).

	Altitude 130 m											
No.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1978 [1]	44.820	1.850	0.269	0.047	0.000	0.000	0.000	0.000	0.504	0.679	0.000	5.362
1979 [2]	0.038	0.000	0.000	0.000	1.041	0.000	0.000	44.009	0.000	0.000	0.000	0.000
1980 [3]	12.620	3.770	0.022	117.798	0.000	0.000	0.000	1.111	0.000	0.000	0.000	0.002
1981 [4]	0.000	0.000	0.000	0.000	12.445	0.000	0.951	0.000	0.000	4.358	15.622	0.630
1982 [5]	17.316	0.000	1.093	0.012	0.000	0.000	0.000	63.216	0.000	0.000	0.000	0.000
1983 [6]	0.000	105.040	0.180	0.000	0.000	0.000	122.030	2.731	0.000	0.470	4.828	86.722
1984 [7]	31.880	1.620	0.000	0.000	57.870	32.000	28.120	26.960	59.270	26.960	3.020	11.730
1985 [8]	0.000	6.770	2.670	0.569	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1986 [9]	0.000	0.000	11.963	0.001	0.000	0.000	0.000	0.000	2.431	0.000	0.000	0.000
1987 [10]	78.905	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	28.163	0.000	2.454
1988 [11]	0.000	0.000	0.000	32.126	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.896
1989 [12]	0.000	0.000	154.962	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1990 [13]	0.000	0.000	0.000	8.912	0.000	0.000	0.000	0.000	0.000	0.068	5.753	4.415
1991 [14]	0.000	0.000	0.000	46.612	0.000	0.000	7.550	3.639	0.000	8.288	16.361	0.000

Peak Flow of the Year was: (1) 219 cms on Dec. 25; (2) 235 cms on Aug. 10; (3) 155 cms on Apr. 8; (4) 185 cms on Nov. 3; (5) 120 cms on Aug 14; (6) 668 cms on Feb. 17; (7) 364 cms on Aug. 28; (8) 15.5 cms on Feb. 10; (9) 20 cms on Mar. 26; (10) 240 cms on Jan. 16; (11) 274 cms on Apr. 22; (12) 300 cms on Mar. 21; (13) 51.5 cms on Dec. 19; (14) Not calculated.

Figure 3.29:

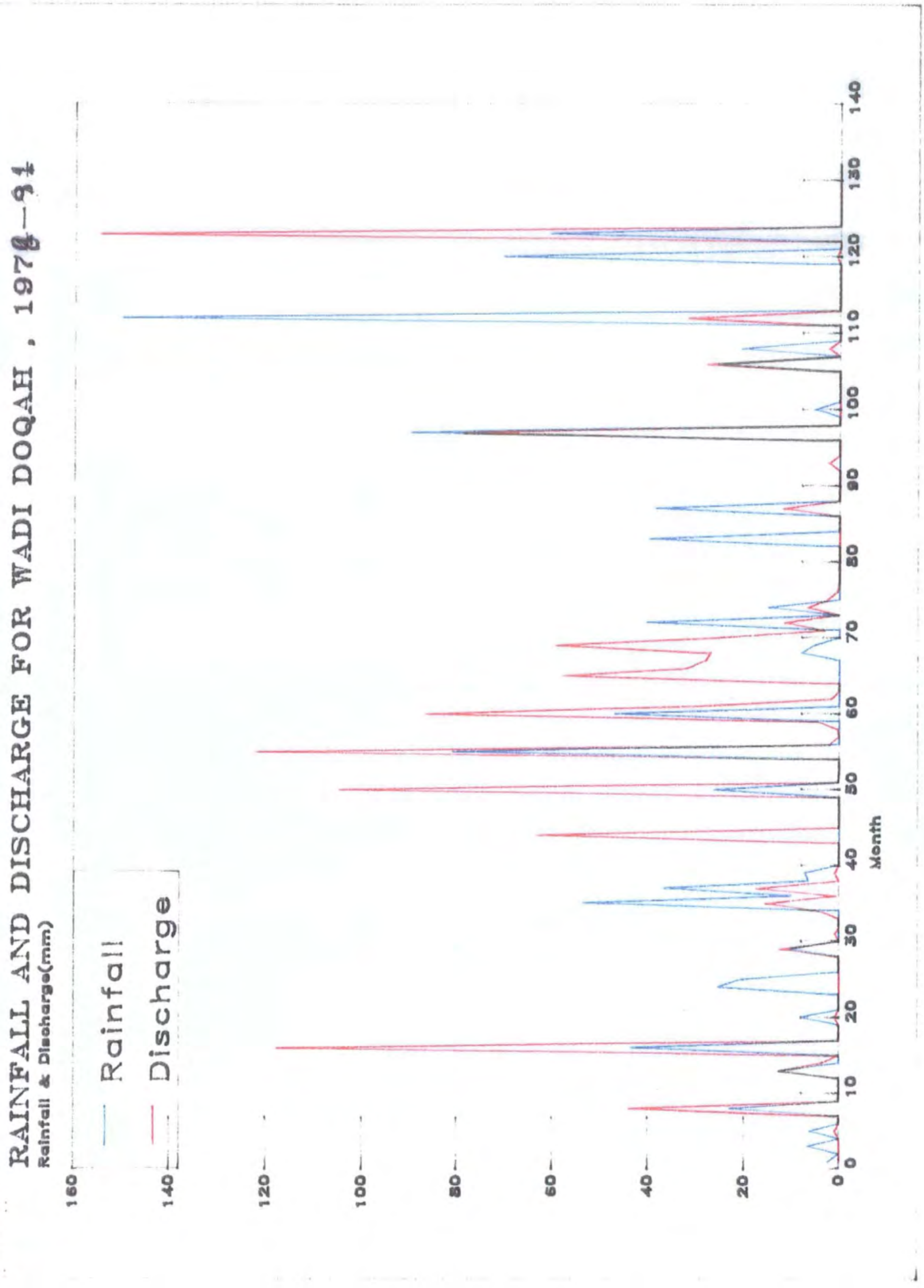
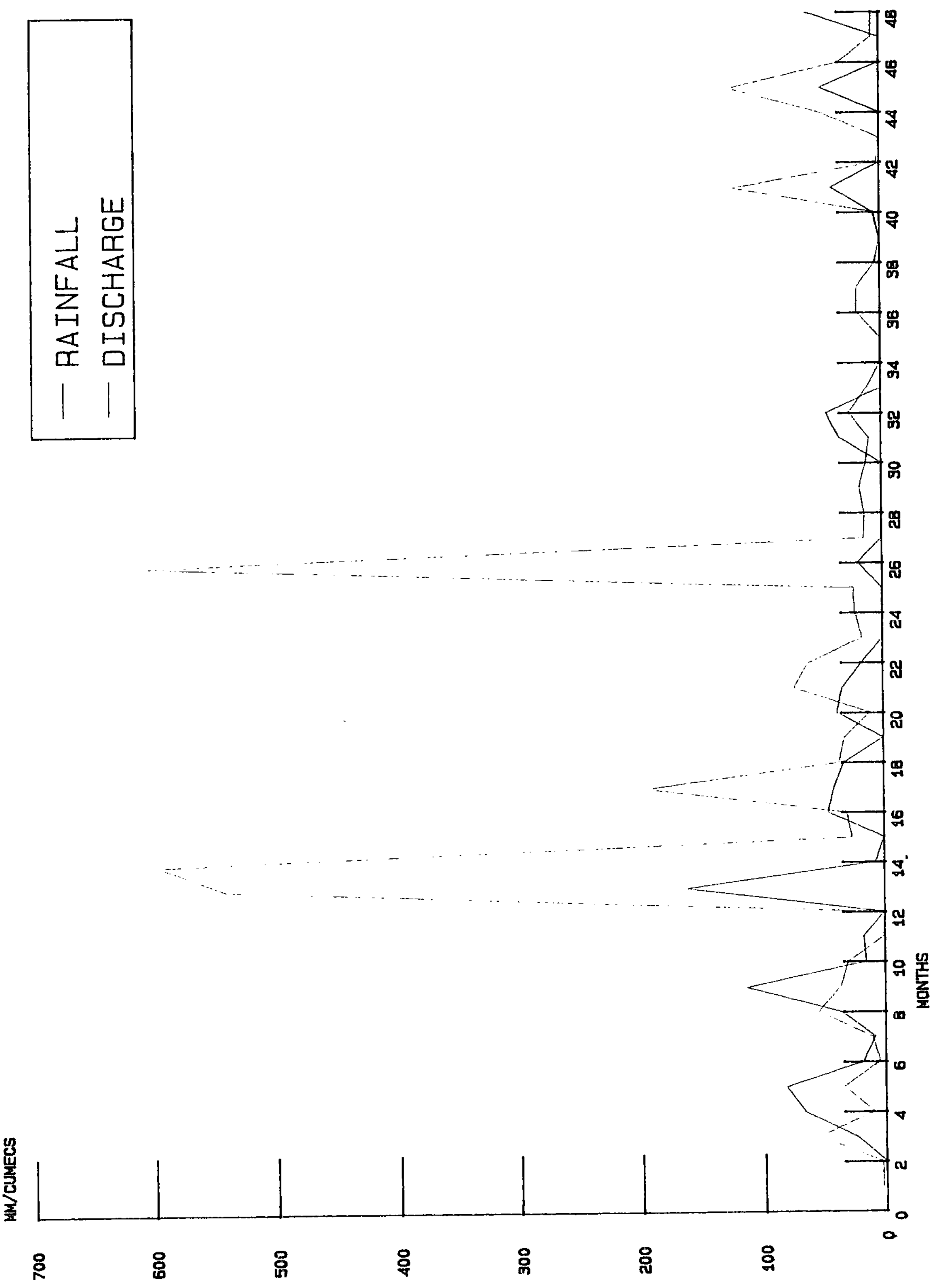

RAINFALL AND DISCHARGE FOR WADI DOQAH
Rainfall & Discharge(mm)
Rainfall
Discharge
Month

Figure 3.30: *Rainfall and discharge for Wadi Hali, 1978-1991*



The dashed lines represent the accumulated percentage of the mean monthly rainfall and run-off. This would be an ideal case for keeping the volume of stored water in the reservoir to its minimum and hence minimising the losses. The monthly periods are more realistic and each consecutive month constitutes a distinctive feature rather than the individual years. This is due to the fact that the storm events producing run-off vary with the time of occurrence and a two month period would give more time than one month period for its movement with respect to time, and shows a fairly constant rate of discharge in many years (13 years) which would have to be put down to base flow. Rates of through flow would be fairly high which, combined with the return flow groundwater reserves, would ensure a steady input into the wadis, rising proportionately with previous rainfalls.

There is some evidence from the graphs that suggests that the patterns of rainfall and discharges can be closely related (especially in Wadi Doqah). However, there are significant anomalies, notably where the discharge figures can appear higher than the rainfall figures.

Each of the wadis indicate a different pattern when the available information is graphed. The graph for wadis shows continuous discharge over a three year period, and this pattern is distance mimicked by the pattern of rainfall measured over the corresponding period.

The amount of water discharged monthly by the areas of the peak upstream of the wadi channels increases during the monthly rains (January to May), From 750 cms in December, it increases to 6000 cms in February, depending on the year, that the rainfall was heavy, year to year. These discharges equal about 41% of the annual water discharge at this gauge. The reason for the delayed flood peak which occurs at wadis compared to that at Wadi Jizan is because of the high discharges of water towards the sea, the speed of water and type of soil. In the dry seasons, the water discharged from the stream into the dam in Jizan is also low.

The graph for wadis, such as Wadi Baysh, shows continuous discharge with 3 noticeable peaks. In the early months of each of 3 years, but the rainfall measured in that area is very low and discontinuous.

The discharge reflects the change in rainfall levels, with the highest level of discharge recorded in one of the driest months of the period.

The run-off data for the 14 year recorded period was listed in descending order, giving the highest runoff value number 120-6 and the lowest number 90-14. Then, formula 120 was applied to the monthly runoff and the frequency distribution curves were drawn on a logarithmic probability, which also includes frequency distribution curves for the bi-monthly runoff.

Another interesting finding of this area is that the time-lag between the time of occurrence of a rainstorm and the time of arrival of the corresponding surface water in Tihama Asir is less than 24 hours.

This measures run-off from the entire surface of the drainage basin. However, to describe accurately the run-off from a drainage basin, the environmental characteristics that affect run-off should be known and accounted for. Interpretation of wadi flow records have generated a considerable body of hydrological and engineering literature. The purpose is to keep a record of wadi stage and to anticipate the arrival of the flood wave that sweeps down the wadis each rainy season from the Asir Mountains. Located at strategic places along the wadis, 19 gauges record the crest-stage, and alert the farmers awaiting the water for their farmland. Measurement has been found necessary not only of the water level, or stage of wadi, but of the total flow volume as well.

The runoffs were taken without accounting for evaporation or infiltration before it reaches the wadi channel. In some parts of these catchment areas, evaporation can account for up to 93% of water loss. The irregularity and intensity of water flow in the wadis might have an effect on the carrying capacity of the wadi, for example by a change in the shape or friction of the channel.

Most of the surface water comes after the rainfall on the Asir Mountains and runs to the Red Sea, and from local rainfall. Sometimes the basin has high surface water but other times there is not enough rainfall to produce much surface water, such as Wadi Baysh Basin in 1984, because when the rainfall comes in the end, the rainy seasons, or after the dry season.

Conclusions

Regarding resources on a year on year basis, the hydrological record shows, since the natural supply of water is in only a minor way subject to development activity. There are, however, major fluctuations on a day to day basis in such phenomena as precipitation and stream flow.

The hydrological record provides an interesting overview of various resources and it should give the layman a basic understanding of Saudi Arabia's water problems. However, the summarised, general and incomplete presentation of the data do not make the hydrological record suitable as a scientific data base. It is, therefore, unfortunate that the foreword to the technical reports prepared for the MAW are not freely available for public distribution. This means that future researchers will be as poorly informed as their predecessors.

The relationship between rainfall and runoff is of the same nature as that of the monthly relationship, the daily inflow into wadi reservoirs is proportional to the square of the daily rainfall over the catchment areas. This gives a good indication of the characteristics of wadi catchments and the integrated factors involved in the rainfall, surface runoff relationship.

To study the hydrology of Tihama Asir and correlate surface run-off to rainfall, knowledge of surface flow discharge into reservoirs through the different tributaries and its variation through time and space is necessary. This can be achieved initially by installing six water level recorders, one just up-stream and the other five at reasonable control sections on each of the wadis contributing to Tihama Asir, namely Wadis Jizan, Baysh, Dogah, Hali and Dammad, up-stream of the highest water level of the reservoir.

The data derived from the wadis operation is invaluable not only to one wadi municipality, but all regions in contributing a clarification wadi runoff hydrology through analysis of generalisation of physical regional phenomena. A hypothetical method applied here to explain the runoff system of the wadis consists of concept of soil moisture to be introduced and coefficient of runoff to be controlled by soil moisture which concept is commonly used surface runoff series from rainfall records. As runoff values to be related to rainfall. Four periods are selected. There periods in 1987, 1983 as Tables 3.9 and 3.10 show, in which the peak flow is 6,000m^3/s in February, and 668m^3/s in February.

Consider a hydrologist with the problem of estimating peak flow frequencies and runoff on a small ungauged stream. The designer could use one or more of the following:

1. Records of nearby gauged streams might be transposed.

2. Records of rainfall might be used together with regional rainfall-runoff relationship and a synthetic unit hydrograph used to reconstruct streamflows.

3. Flood peak formulas might be applied.

The amount of time that can be devoted to hydrological study in advance of the design of a small hydraulic structure is limited.

The need for the construction of dams have emerged to control the runoff and sudden floods to avoid the damages of floods that may wash out properties and people. Also the dams retain the water to be directly used either for domestic or irrigation purposes or recharge the aquifers.

The types of dams constructed by the MAW are: rockfill and concrete dams. The MAW has persisted since it was established to construct dams. Therefore between 178 and 200 dams of difference volumes and types have been constructed in Saudi Arabia. Also the storage capacity of the erected dams is variable. Wadi Bisha Dam is more than 110m high and has the largest storage capacity of 325mcm, Wadi Najran Dam has the storage capacity of 85mcm and Wadi Fatima Dam of 20mcm. The MAW plans involve a lot of dams that have a contemplated programme to be implemented in the future. As a result, several dams and reservoirs have been constructed or planned, in order to regulate the wadi flow.

Extensive alluvial fans are observed in the lower courses of the important wadis such as Wadi Al-Dawasir, Wadi Al-Aflaq, Wadi Jizan and Wadi Baysh. The development of water resources of the wadis integrated with the land use irrigated agriculture. This requires an assurance of a continuous flow of dependable data, which may include rainfall, surface runoff and infiltration, as well as irrigation water released at different control points of the distribution system. The estimated amounts of runoff are converted in mm depth for the basin, and those rainfall to be corresponded to each runoff are sought applying soil moisture described in area.

Water pollution in Saudi Arabia has not yet become a serious problem, due mainly to the absence of large industrial complexes and the associated range of noxious effluents which they produce. The problem of water resource pollution around the large cities of the country has already given rise to some concern as the result of contamination from sewage effluents. With growing industrialisation, it seems inevitable that pollution will be an increasing threat to water resource development.

The temperate climates where drainage densities are significantly higher than in the country the number of sites where even limited size dams can be built is restricted therefore in this region, it may prove difficult for this alone to construct the number of dams which would be required to allow recharge at the levels planned to go ahead.

More correctly, monthly rainfall for the basin area should be read as (rainfall-runoff) and evapotranspiration, monthly representative of the basin, tentatively monthly pan-evaporation multiplied a constant, should include a permanent loss of deep infiltration. In this region, however, annual runoff hardly exceeds 10% of annual rainfall, and in the sense as a first approximation, the runoff is made following the heavy rainfall over the mountain.

Chapter Four

Groundwater

Introduction

This chapter studies the occurrence and distribution of groundwater in Saudi Arabia and in Tihama Asir. The principal aquifers in Saudi Arabia are identified, and their water quality is discussed. Aquifers which are locally important are also identified, and their water quality and distribution in Saudi Arabia are discussed, including their development for domestic water demands and for irrigation supply. Groundwater movement as a result of groundwater withdrawal is examined, along with use regulations after recharge by runoff. The quality of groundwater is studied in the context of pollution. The wells drilled to meet water demand and development use are also studied. Groundwater and aquifers in the Tihama Asir are examined, with regard to their distribution and development.

Hydrogeology may be defined as the study of groundwater occurrence with emphasis on geological environment in which groundwater resides. Groundwater residence or flow in the lithosphere governs its quality, not only through the mineralogical composition of the lithologies, but also by the degree of its movement in shallow or deep strata. The synthesis in this chapter treats groundwater occurrence in the various aquifer systems, its flow and level fluctuation. The aims of this chapter are to unravelling the different geological conditions that govern groundwater availability and quality, with the objective of portraying a clear knowledge of the hydrogeologic environment to understand the complex physical setting of the groundwater resources and aid in the appraisal of their status and management, and to evaluate the potential groundwater resources of the country regarding water quantity and quality. Hydrological nomenclature is defined so as to comprehend the various values cited in the text that describe aquifer. The aquifer systems of Saudi Arabia are identified and the composition of the material in which they occur is described in detail in order to highlight the geological in groundwater occurrence so as to explain groundwater deficiency and underline the confused priorities in its abstraction and use. There exists no countrywide explanatory description of the hydrogeology of every region in Saudi Arabia, and the detailed areal treatment presented in this chapter has been necessitated by the need to produce a comprehensive appraisal of the water resources of Saudi Arabia. The main hydrogeological units of Saudi Arabia conform with the main topographical regions..

Groundwater hydrology may be defined as the science of the occurrence, distribution, and movement of water below the surface of the earth. It is water which occurs beneath the surface of the earth within saturated areas where the hydrostatic pressure is equal to or greater than atmospheric pressure. This precise definition is useful in distinguishing between groundwater and other types of subsurface water, such as capillary water or soil water.

Waterbearing formations of the earth's crust act as conduits for water transmission, and as reservoirs for water storage. Water enters these formations from the ground surface or from bodies of surface water, after which it travels underground slowly until returning to the surface by natural flow, the action of plants, or the activities of mankind. The storage capacity of groundwater reservoirs combined with small flow rates provide large, extensively distributed sources of water supply.

The main source of groundwater is meteoric water, that is precipitation, has been recently involved in atmospheric circulation. The other source, though of secondary importance, is connate or fossil water, that is water which has been out of contact with the atmosphere for thousands or even millions of years, and that has not necessarily remained static since the burial of the surrounding rocks but has migrated many miles

(Abdul Aziz, 1984). The meteoric water source includes all replenishable groundwater in the Quarternary aquifers, while the connate water source includes the non-replenishable deep formation aquifers such as the Upper Cretaceous and Tertiary sequences of the aquifers that have already been reached by deep drilling in various parts of Saudi Arabia.

An assessment of a water resource is related, of necessity, to the rate at which it can be mobilised. Abstraction of deep groundwater is limited by drilling technology, and by the rate at which the users are willing to invest in extraction facilities. In other words, one generation may deplete Saudi Arabia's major water resource, but this depletion time estimate depends very much on the development strategy.

In the study, shallow groundwater is understood to occur in isolated aquifers consisting of wadi alluvium, which is periodically recharged by infiltrating wadi flows.

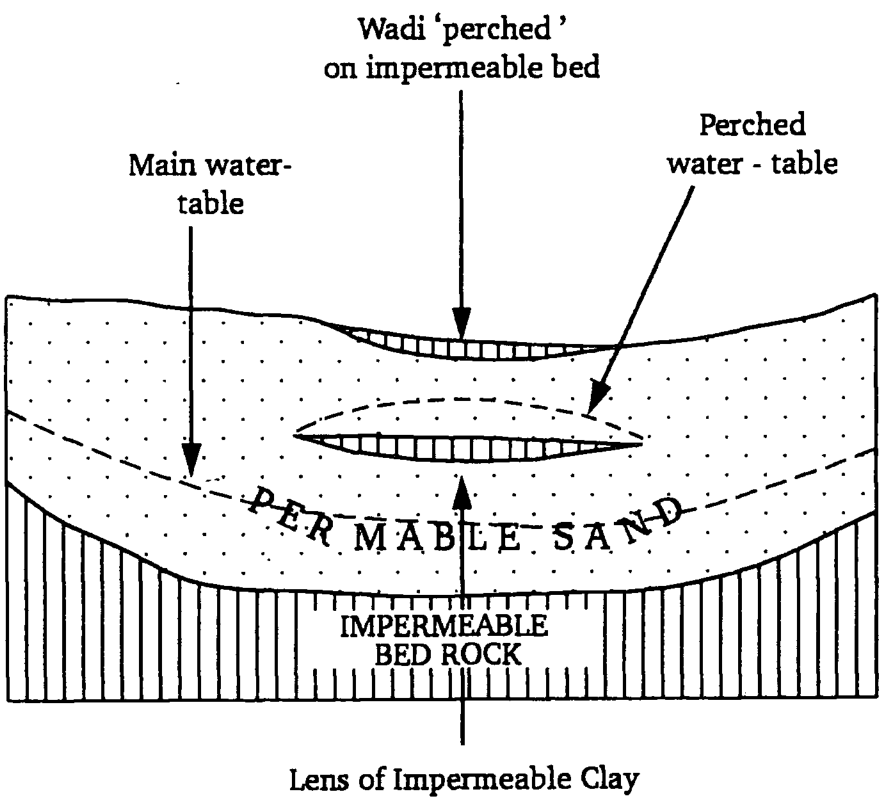
Saudi Arabia's groundwater resources are stored in aquifers. Various types of substitutions will be required to maintain their long-term availability by recharge. These aquifers currently supply over 70% of Saudi Arabian water needs.

Whilst renewable groundwater supplies are estimated to continue at levels of around 9,520 mcm/y, the intensive development of aquifers has resulted in a rapidly rising rate of depletion of this valuable resource. Proven resources from the seven principal aquifers amount to 33,500 mcm.

Figure 4.1 shows the groundwater situation in an area where withdrawal recharge is illustrated, the reserve in dead storage is water that would not recharge naturally even if recharge stopped entirely. Water in an aquifer cannot be seen and its amount cannot be measured directly. Every aquifer is unique and requires individual evaluation.

A groundwater level, whether it be the water table at an unconfined aquifer or the piezometric surface of a confined aquifer, indicates the elevation above atmospheric

Fig. 4.1 A Perched Ground Occurs in the Subsurface.



pressure of the aquifer. Any phenomenon which produces a change in pressure on the groundwater will cause the groundwater level to change. Where necessary, man can control groundwater levels to suit his purpose. Regulation of seepage through earth dams and land drainage are examples of such control (see Chapter 3).

Sometimes a localised confining layer lies above a lower continuous confining layer, the result is an independent area of 'perched' groundwater, lying above the water-table proper and separated from it by unsaturated rocks. The localised confining layer is usually caused by a lens of impermeable clay laid down in a former stream channel.

Water levels do not rise or decline uniformly throughout an aquifer when a change of storage occurs.

4.1 Hydrology of Aquifers

First we look at the lithology of all the sedimentary formations of Saudi Arabia. Attention is drawn to the two main types of sedimentary aquifers, the sandstone types and the carbonate types. Thereafter, the nine major sedimentary aquifers of the country are described in some detail with respect to their stratographical position, lithology, thickness, depositional environments, as well as some of their hydro-geological characteristics. But the amount of groundwater held in them, as well as their state of development, is reserved for more explicit treatment in this study on the groundwater resources of Saudi Arabia.

The sands predominate in the old sequences, while carbonate rocks become of increasing importance in the younger sequences. As a result, the sandstone aquifers are found in the west, commencing at• the edge of the easement outcrops and extending eastwards/ As one moves east, however, the carbonate aquifers become of increasing importance. Since the groundwater also moves from east to west, there is thus a tendency for water to move from the older (and often deeper) sandstones into the carbonate aquifers wherever there are gaps in the intervening aquicludes. In the east, also, sea level forms a base to uphold groundwater, while topographical elevations decrease, as a result groundwater is found much closer to the surface in the east than in the west - with the exception of water in alluvial infill in wadis of course.

In this, detailed descriptions are given of the actual development and water resources of the nine major aquifers of the country. It is felt that the development of the Neogene and Quaternary aquifers is so much a local affair as not to warrant inclusion here. This by no means underrates or ignores the local importance of the valuable groundwater resources transmitted through, or held in, these shallow, readily-tapped unconsolidated aquifers.

In this portion of the paper, considerable use has been made of the report prepared by MAW Department of Water Development, 1990, in particular "Outlines of Groundwater Resources of Saudi Arabia".

4.2 Occurrence of Groundwater

The main source of groundwater is precipitation, or water that has been recently involved in atmospheric circulation. The other source, though of secondary importance, is fossil water, that is, water which has been out of contact with the atmosphere for thousands or even millions of years, and that has not necessarily remained static since the burial of the surrounding rocks but has migrated for many miles. The meteoric water source includes all replenishable groundwater in the Quaternary aquifers, while the connote water source include the non-replenishable deep formation aquifers.

The interstices in the zone of saturation (the aquifer) are field with water, which is described as groundwater. The top of this saturated zone is in effect the water table. Above the water-table, up to the ground surface, is the aeration, where the interstices of the soil particles are occupied by both air and water in places where the water-table is high and close to the surface, as in most inland sabkhas.

Hydrological and hydro-geological investigations were commenced in the early, and the principal aim of these has been to determine the amounts, distribution and quality of water resources of the study upon which the development may be based. The field investigation involved the measurement of rainfall, evaporation, runoff, groundwater extraction, water quality, and water table fluctuations.

The measurement of runoff posed considerable problems because of the peculiar runoff characteristics in most wadis. Small floods are rapidly absorbed by the wadi bed gravels and in certain wadis, the discharge varies constantly along the length with a series of increments from tributaries superimposed upon a steady decline by infiltration which, from observation.

Groundwater extraction was measured in two ways: from the water point inventory carried out by the hydro-geological team and from estimates made by the agronomists. Water quality was determined by conductivity measurements in the field and full chemical analyses were conducted on 406 representative samples of well. Water table fluctuations were observed regularly at 80 wells by sounding methods and in the main aquifer systems the water level at a number of salient wells was observed continuously by automatic water level recorders.

4.2.1 Occurrence of Groundwater in Saudi Arabia

In order to describe the occurrence of groundwater, features relating to the physiography of the country need to be determined (see Chapter 2). Geological features important to groundwater must be identified, in particular their structure in terms of water-holding and water yielding capabilities. Assuming that hydrological conditions permit the supply of water to the underground area, the characteristics of the subsurface strata govern the distribution and movement of the water. The role of geology in groundwater hydrology cannot be overemphasised.

Although the groundwater of the country can be described according to stratigraphic units, they are by no means homogeneous in extent, character and properties owing to local and regional geological dislocations by folding and faulting that cause changes in faces. This has resulted in a highly complex lithostratigraphic situation that negates correlation of a water-bearing strata with another one nearby.

The basement complex rocks of Precambrian age, cover the southern and western area of the central region of Saudi Arabia. They are characterised by shallow, limited groundwater formations mainly existing in certain wadi deposits. Water of these shallow water formations varies in quality and quantity depending on the annual rainfall. The other two thirds of Saudi Arabia that is covered by sedimentary rocks, contains most of the important groundwater formations in Saudi Arabia. Aquifers in the western and southwestern regions of Saudi Arabia can be subdivided into four main groups. These are:

1. Surface aquifer deposits that occur in the main wadis consist of gravel, sand, silt and clay grains, and constitute the most important water formations of the Arabian Shield. The depth of these formations ranges between 12 to 50 metres and may extend over the length of a wadi.

2. Sub-basaltic aquifers in lava basaltic sheets. These are interconnected basalt and alluvium formations, the depth of which ranges from 40 to 70 metres. Water quality is good and dissolved solids range between 700 to 2,500 ppm while discharge ranges between 60 gallons/minute and 500 gallons/minute (MAW).

3. Weathered and fractured bedrock formations occur mainly in the Eastern Region of the Arabian Shield but quality and quantity are poor due to the low water retention of these rocks.

4. Alluvial deposits of Tertiary or Miocene age near the Red Sea Coast. Water quality is very poor.

The groundwater occurrences in Saudi Arabia can be divided according to their geological situation into a number of types. There are the enormous underground aquifers in the cuesta landscape of the Shelf, and the reservoirs in the thick bodies of sediment in the northern part of the country. The coastal landscapes along the Red Sea have hinterland wadis with sediment fillings, although their capacity varies with precipitation and size of the catchment area, they usually offer unconfined groundwater, the largest amount of which is to be found in the vicinity of Jizan.

The highlands, elevated in the recent geological past, show an extreme scarcity of water in the extensive volcanic plateaux. In the crystalline rocks, however, there are minute oases in the uppermost roots of the wadis. Water is taken from wadi basins at medium altitudes for large settlements. Groundwater under basalt flows are also significant.

Throughout much of the higher western parts of the country, igneous and metamorphic rocks outcrop to form a resistant and rigid basement complex of largely Pre-Cambrian age. The permeability of such rocks is low and so groundwater tends to concentrate in patches of alluvial deposits along the lines of the major valleys. This water can normally be tapped by shallow wells, but the quality and yield from such aquifers can vary considerably, dependent on local environmental conditions. There is a tendency for it to become more saline as the coastal plain. Occasionally major springs are found issuing from solid rock outcrops within this region and, where these occur, settlements have grown up.

4.2.2 Groundwater Development

The probable water balance is illustrated in the active drainage catchments. On the other hand, the groundwater development possibilities are limited to a number of specific areas where there are favourable soil, extraction and water quality conditions. For instance, the basins of the western watershed contain, in the lowest parts of the lower course, groundwater with salinity generally higher than 3,000 ppm and unsuitable for human and agricultural purposes. On the other hand, in the upper parts of these basins it is possible to use but limited quantity of groundwater, despite their excellent quality, due to the lack of agricultural soils or because the water is stored in alluvial areas of limited extent. The groundwater development potential is interesting, however, in those parts of the wadis where there are extensive alluvial areas, favourable morphological conditions for the infiltration of flood waters, and where the quality of the groundwater is satisfactory.

4.2.2.1 Groundwater and development in Saudi Arabia

The oases of Saudi Arabia and the Arabian Peninsula are based on groundwater, which has been developed and used from time immemorial. Such early development was not the result of any conscious investigation but would have been based on improvements of existing springs and seepages. In many areas, and in particular throughout the great sedimentary basin at eastern Saudi Arabia, natural springs and seepages are led by groundflow under pressure in the in the underlying aquifers. From excavating springs to improve their flow, to the construction of wells which cut an artesian aquifer and so flowed is a short step, today old springs, ayns and old flowing wells are hard to distinguish. Since the depth of groundwater was normally smallest in depressions, the oases tended to occur in depressions, thereby raising the problems of waterlogging and salinity with limited drainage possibilities.

Modern development went hand in hand with oil exploration and development in eastern Saudi Arabia. Exploratory geological drilling, test drilling for oil and groundwater investigations and development all go hand in hand, and complement each other. Aramco drilled its first water supply well in Dhahran in 1936, and flowing artesian water from the Alat and Khobar members of the Dammam formation. Many wells penetrated the Alat aquifer and sometimes the deeper Khobar aquifer with no casing provided or with a stub of casing driven into the soil.

Development of groundwater by modern drilling equipment spread quickly to other areas of Saudi Arabia. In part this water was required for drinking supplies, but also to expand and improve existing oases. The number of areas where artesian water would flow from such boreholes proved to be surprisingly large. This in turn spurred additional drilling and extraction. As may well be understood, many of these boreholes were improperly constructed, and produced as much waste water as they did water which could and was properly utilised. Likewise, there was no idea as to the amount of groundwater available for development and used. Even at government policy level, where the distinction between fossil and current groundwater and between mining at groundwater and maintaining extraction equal to replenishment, were well understood, and where the need to prevent waste of a natural resource with concomitant waterlogging and salinisation were recognised, lack of firm data inhibited action.

To stop legitimate development would retard the development of the country, to allow controlled extraction would result in overall depletion and diminishing supplies of this precious natural resource of the country and of its people.

Since a groundwater resource can be defined as a naturally- occurring water which can be developed and used to satisfy man's needs in a manner conferring an overall net benefit from its use, groundwater resources are not a fixed quantum but are ever changing and responding to an interlocking set of conditions. Of these, the main conditions are:

a. man's needs (including those of his animals, irrigation, factories, transport, recreation and related uses);

b. limits of use dictated by the physical and chemical and organic condition of the water;

c. techniques of location and extraction viewed in both the physical and cost aspects;

d. techniques of use and improvement, as salt-resistant cultures and demineralisation techniques; and

e. the overall cost/benefit ratio using this term in its wider aspect of overall improvement of conditions of living for an individual, a tribe or a nation.

In the light of these two basic conceptions, that groundwater is a resource only in relation to man's needs and abilities, and that groundwater is a component of the hydrological cycle renewable by infiltration where such occurs.

Development of natural springs is not of major importance in Saudi Arabia. Development by drilling is carried out, and drilling in particular has benefited from close association with oilfield operations. The depth of drilling is often great (up to 2,400m), calling for large rigs and excellent control. The confined nature of many of the aquifers means that casing, screening and cementing must be carried out by most modern techniques to avoid subsurface transfer from high-pressure to low-pressure aquifers, to avoid mixing of good-quality groundwater with brackish or saline water, and to prevent upwards seepage outside casings leading to water-logging and soil salinisation around boreholes.

Flowing artesian boreholes also present development problems, what at first may appear to be a valuable find of flowing groundwater can, by improper development (and management), become a source of groundwater waste and land deterioration. The principle of step by step development, which is feasible for groundwater and confers not only technical but economic benefits, is followed in Saudi Arabia.A large portion of Saudi Arabia is covered by the Quaternary deposits. However, groundwater of the aquifers are usually used for municipal and agricultural purposes, although increasing water demand of the cities has restricted agricultural practices to limited areas in the upstream reaches of the aquifers. There has been an increase in the demand for water in recent years, that water demand increased from 8830 to 15290 mcm/y between 1985 to 1990. This amounts to a 264% increase over a five-year period (MAW). Water demand is projected to reach more than 20,000 mcm/y in 2010. The rapid growth of demand for water has created a significant imbalance between water needs and the availability of renewable water supplies.

The unprecedented growth of the cities of Saudi Arabia brought an enormous nationwide demand for groundwater. Furthermore, projections made at the time indicated that continued rapid population growth in the urban centres, and the existence in the Saudi Arabia of fertile land remaining to be irrigated would lead to even greater groundwater requirement through the year 2000. Fortunately, the country has available large groundwater resources. About half of this water is stored in aquifers the proximity of which to major use areas permits them to be developed economically.

Some of the waters of the main groundwater aquifers accumulated over 30,000 years ago. The recharge rate of these formations from rain is negligible. Water formations occur at different depths and sometimes overlap each other.

Groundwater uses other than for agricultural and domestic purposes include injecting water into oil fields in order to push petroleum to the top. The first project in Saudi Arabia for maintaining oil reservoirs through water injection started in 1956, in the Abqaiq field, from Wasia Aquifer. Around 1960, experimental projects were started in the Ayn Dar and Shedgum area of the Ghawwar field, from Biyadh Aquifer. In 1973, a pressure maintenance programme was started in the Khursaniyah and Berri-fields, from Wasia Aquifer. Supply wells were located in Abu Ali island and Uthmaniyah area.

One of the most important formations is the Umm-er-Rudmah formation, which is considered to be the most prolific. It extends from the Iraqi border in the north, to the Rub'al-Khali in the south. The Wasia aquifer in the north eastern part of the country is rich, but development will be costly, because the water is around 762 m below ground level. In the sedimentary basin, a depth of 61-244 m often yields flowing artesian water with a capacity of 264,172 m^3. The south eastern part of the country has similar aquifers (MAW).

The deepest fresh water produced is in Turabah in the Saq formation in the north west at a depth of 2,252 m. It yields 500 m^3/minute (MAW and Noury, 1984).

The general movement of groundwater in the sedimentary formations is in the form of a down-dip to the east, bringing the greatest concentrations of water into the east where the springs occur inland at Al-Hasa, along the coast at Qatif, beneath the water of the Arabian Gulf and on the offshore islands. Water quality deteriorates towards the east and the north, from a few hundred parts per million (ppm) to very high levels.

The sedimentary basin of the country contains the water bearing formations and is composed mainly of sandstone, limestone, shales, marls and alluvium. The deposits of this basin are divided into 28 formations, 20 of which contain varying quantities of groundwater. Recent surveys have proved that at least 9 of them, which cover very large areas, can be considered prolific aquifers.

The unprecedented growth of the cities of Saudi Arabia had led to an enormous nation-wide demand for ground-water. Furthermore, projections made at the time indicated that continued population growth in the urban centres, and the existence in Saudi Arabia of fertile land remaining to be irrigated would lead to even greater ground-water requirements through the year 2000. Fortunately, Saudi Arabia has large available ground-water resources, but half of this water is stored in aquifers whose distances from major use areas permits them to be developed.

In eastern Saudi Arabia, oil companies injected water through intake oil wells. The water was obtained from two sources:

1. **The Wasia Aquifer:** 1,370 m below land surface; the average temperature was about 77°C, and the rate of production ranged from 5,000 to 8,000 litre/min.
2. **The Biyadh Aquifer:** 1,615 m below land surface; the average temperature was 82°C, and the rate of production ranged from 15,000 to 28,000 litre/min.

For centuries, limited sources of shallow groundwater, in the Basement complex and over the country as a whole, were able, most of the time, to keep up with the water needs of the people in the region. Human and agricultural consumption of water was minimal.

4.2.2.2 Groundwater and development in Tihama Asir

Groundwater in the alluvial deposits of Tihama Asir is exclusively recharged by percolation of surface water which is brought down by the wadis from the mountainous areas. The quality of the groundwater is very heterogeneous within the aquifer.

The direction of the groundwater flow is roughly parallel to the wadi beds, this means a general direction from the north east to the south west, from the foothills towards the sea.

The piezometric gradient varies from 0.5% in the upper parts of the wadi to 0.07% at the beginning of the coastal deltas. The seasonal variation of the groundwater table in wells depends on the location of the well.

The crystalline rocks and volcanic deposits in the area. The major aquifer of the area is the alluvial sediments of the coastal plain. These are of variable thickness at up to 100m, with an associated groundwater table that varies from a depth of as little as 3m below the wadi bed, up to 25m in some locations further from the wadi. The precise nature of this aquifer is difficult to estimate in the absence of more detailed borehole records. The deposits are very heterogeneous, involving the juxtaposition of very coarse and very fine layers, so that the possibility of sealed aquifers at depth cannot be ruled out. The hydraulic relationship between the alluvial deposits and the underlying strata is also unknown and will remain so until more borehole information is available.

The recharge capacity of groundwater is a matter of some speculation. It would be likely to vary considerably from year to year dependent on the rainfall and flood distribution. It is unlikely that any recharge occurs directly from rainfall. Virtually all precipitation in the coastal plain goes to satisfy the soil moisture demands of the soils or is subsequently evaporated.

Groundwater circulation in Tihama Asir consists of:

1. Inflow of thermal water along fault lines. This phenomenon is linked with very special conditions and is solely of local interest.

2. Water circulation in the altered areas of the crystalline and metamorphic formations and in the alluvial layers covering them. This phenomenon is probably very widespread in the high mountainous part of the basins. The permeable layers are generally very scattered, and the springs originating from these drains generally have a limited discharge.

3. Water circulation linked with areas of intense fracturing in the crystalline and metamorphic formations. These areas may drain off the foregoing water or affect a relatively extensive basin. In special cases the drainage would be reflected in springs with comparatively high discharges.

4. Water circulation linked with the permeable layers of Quaternary basalts (Al-Birk area). Such water is probably limited to old fossilised forest beds, filled by lava flows and still acting as drains for groundwater. However, supply seems to be limited due to the small extent of the basins and the low rainfall of the area.

The alluvial cover of the wadis and the coastal plain is the site of this aquifer, which is continuous and regularly fed by the surface water during the floods of the wadis. The resources in this aquifer are dependent upon the size of the alluvial reservoir.

In this alluvial reservoir the discharges able to be tapped diminish and the chemical quality of the water drops as one moves away from the point of the wadi outfall in the plain, because the waters spread over an area which becomes wider and wider. The speed of their flow diminishes considerably with the lessening of the piezometric slope and of the permeability. Evaporation increases downstream with consequent increase in salinity, and finally just a very small part of the original underground flow reaches the area.

When run-off infiltrates into the subsurface it becomes groundwater, then re-emerges at a different point as a spring to provide base flow in a wadi.

Most natural discharge occurs as flow into surface water bodies, such as runoff to the surface appearing as a spring. Shallow ground-water may return directly to the atmosphere by evaporation from within the soil and by transpiration from vegetation.

In the northeast, the aquifer is, more or less, limited by the outcrops of the basement and the dyke complex respectively. In principle, it forms a flat trough-shaped body with a longitudinal axis trending from northwest to southeast. The axis line at which the alluvials have developed a maximum thickness of at least one hundred metres seems to be located along the Jizan flexure in the centre of the plain. East of the axis line the aquifer generally overlaps the Baydh Formation. To the west, the aquifer overlaps the continental series of the Mansiyah anticline. In the northeast, between Jabal Hatha and Wadi Atwad, the aquifer lies directly on the Miocene dyke rocks. In this area, and east along the northwest-trending Pleistocene fault, the aquifer diminishes rapidly due to the As Sir displacement. Therefore, beyond Wadi Atwad, groundwater occurrence is very limited.

In the eastern area of Wadi Shahdan, the base of the aquifer is the Jurassic Khums Sandstone and the thickness of the aquifer is very small. This is caused by the fact that in this area the most effective fault line of the eastern flexure zone is displaced to the southwest.

As a result of the drilling of 18 exploratory wells, the existence of an aquifer has been shown to be highly heterogeneous in its stratigraphic sequence.

Some 70% of the penetrated water-bearing aquifer material consists of more or less impermeable silts and clays. Due to the As Sirr displacements, this formation forms the bottom of almost dry alluvium in this area.

4.3 Principal Aquifers in Saudi Arabia

The Ministry of Agriculture and Water (MAW) reached an agreement with the Food and Agriculture Organisation (FAO) of the United Nations in 1964 to assist in supervising a hydro-agricultural survey in Saudi Arabia. For the purpose of the survey the country was divided into eight areas. The studies have located many aquifers with large amounts of stored fossil water. The sources of groundwater in Saudi Arabia are comprised of two main formations. The shallow formations contain the rainwater which percolates through sand and gravel layers or along wadi beds. The depth of the formations is between a few metres and a few tens of metres and the water can be tapped by means of wells or, in the lowlands, it can appear in the form of springs. The area with the richest sources of surface water are the wadi beds such as those in Asir and those in the interior, such as in Qassim (Al-Shareef, 1978). However, a continuous reduction and drying up of the groundwater in the shallow formations has been experienced in many areas of Saudi Arabia, posing a great problem to the agricultural and domestic use of water and become a risk for capital investment. Warning is made of many shallow wells, where extraction of water is greater than the recharge to the aquifer. This is the case in some wadis of the Riyadh region. Extraction of water in Wadi Sudair, Wadi Thadiq, Wadi Hanifa and other wadis is also more than the replenishment. The fear is, therefore, that there will not be enough water for irrigation and domestic use unless these aquifers are controlled. The same applies to some wadis in the Asir region. In fact even in the Eastern Provinces, the groundwater level is dropping and there is a fear of shortage of enough water for agricultural expansion.

The deep groundwater formation (aquifers), located hundreds of metres below the surface, is considered to be the most important source of water in the country. Underlying two-thirds of the country are sedimentary formations which store vast amounts of fossil water in aquifers which date from the Cambrian era to the recent age. As the water travels east in a downward trend, the volume and the salinity gradually increase as it approaches the Arabian Gulf. Most of the water from these deep aquifers is brackish water that varies in salinity from 7,000 parts per million (ppm) to 35,000ppm (Noury, 1984). Water treatment plants are necessary to reduce the salinity to about 500ppm which is a level suitable for human use.

In recent times, groundwater recharge has been less than its discharge because of the low average annual precipitation. This has led to a decline in the water level in some aquifers.

There are resources of 950 mcm/y, without further breakdown or location. A value of 2300 mcm/y is used, allowing both for additional artificial recharge and for some recharge to the deep aquifer and water quality, as such Red Sea coastal is storage 14,600 mcm/y and it has poor to good quality water. Taif's storage is 50 + mcm/y, and has very good quality water, as shown in Table 4.1, which gives estimated rates for different areas, and details relating to shallow groundwater resources, including the principal wadis, the magnitude of groundwater resources, and an assessment of aquifers and of water quality. These aquifers generally consist of wadi alluvium, periodically recharged by infiltrating wadi flows. As the volume of flow inceases, so does the depth and width of the flow, giving rise to a deepening and broadening scar as the bed material is shifted. The average annual storage total is about 84,550 mcm/y, and the average annual potential capacity totals about 195 mcm/y. The groundwater recharge rate has been calculated by estimating the underground flow, and the quantity of recharge in proportion to surface runoff.

Table 4.2 shows total storage in the main aquifers, natural recharge and potential resources. Table 4.2 and Figure 4.2 together show that parts of central and eastern Saudi Arabia have an adequate and dependable supply of water available from at least one of the Saudi Arabian principal aquifers. These aquifers range in age from

Cambrian to Tertiary. Six of them are predominantly sand. The water bearing sedimentary sub-strata of the Arabian Shelf are mainly Quaternary deposits. The groundwater in the sediments is recharged by percolation of surface water through wadi beds.

As shown in Figure 4.2, there are eight major confined aquifers: Neogene, Dammam, Umm-er-Radhuma, Wasia and Biyadh, Minjur and Dhruma, Tabuk, Wajid, and Saq. Several studies through the country were conducted to estimate the volume of groundwater in these aquifers (Noury, 1984). A subjective assessment of proven, probable and possible reserves for the groundwater aquifers have been made as shown in Table 4.2. The proven reserve, is the groundwater amount which can be developed with a high degree of confidence given that the aquifer properties are as anticipated. The probable and possible reserve estimates are less certain than the proven reserve. Recharge of these aquifers which mainly comes of leakage from shallow alluvial aquifers and rainfall at the outcrops is of the order of 1.270mcm/y. The aquifers currently supply more than 75% of the country's water need. The country's water requirements between 1985 to 1990 were around 9,600mcm (MAW). This shows that withdrawals far exceeds the natural recharge of these aquifers. The mean amount of recharge is 1,270mcm, the proven is 273,500mcm, the probable is 405,000mcm, and the possible is 750,000mcm in a year (MAW).

The areal extent, geology, hydraulic character, water quality, yield and development of each of the major aquifers differs. The Saq Aquifer and Tabuk Aquifer are the major sources of wells in the central, north and north west regions. The present reserves are 54,000 mcm. The Wajid Aquifer at present supplies water for domestic use and irrigation in the Wadi Dawasir and the Sharawrah area, the storage is 69,000 mcm. However, the greatest potential for development of the aquifers lies in the central south part of Saudi Arabia. The Minjur and Wasia Aquifers are sources in the

Table 4.1

Parameters Related to Shallow Ground-water

Source?

Principal Alluvial Areas	Main Wadis	Catchment Area (km²)	Storage (MCMY)	Potential Capacity (MCMY)	Aquifer Assessment	Water Quality
Red Sea Coast	Jizan, Dhamad, Baysh, Hali, Yiba, Qanunah, Lith, Qudayd/Sitarah, Rabigh, Fatimah, Khulays, Ifal, Aqiq East, Khaybar, Dama	241,600	14,250	105	Limited local development to good potential for future development	Poor to good
Taif-Faidhat Mislah	Wajj, Liyyah, Aqiq	43,200	50+	0	Known aquifers are fully developed, others only of local significance	Generally very good
Asir-Dawasir	Torabah, Ranyah, Bishah, Tathlith, Dawasir	180,000	17,700+	25+	Further development may be possible in certain areas	Good in upper reaches to very poor in plains
Asir-Najran	Najran	39,400	33,350	45	Increased pumpage may be possible in Najran basin	Data available indicates good
South Tuwayq	Jadwal, Mqran	48,300	-	-	No evidence of agricultural development or of withdrawal	No data
Birk-Nisah-Sabha	Hawtah, Nisah, Hanifah, Sabha	162,300	14,100	-	Heavily used in areas, further investigations are needed	Poor to good Generally satisfactory for irrigation
North Tuwayq	Sudair, Meshgar/Nami	152,800	500	0	Important local water supply. Data limited.	No data
Rimah-Batin	Rimah, Rishah, Batin	174,400	4,000	20	Shallow supplies are available, some irrigation	Generally poor. Specific conductivity 2000 to 5000 Mhos per centimeter
Nafud-N.E. Frontier	-	161,000	-	-	Data limited; aquifers very localized. Used for irrigation in Hail area	No data
Sirhan	Sirhan	192,300	600	-	Data limited. Some hand-dug wells	Generally poor. Average TDS 2000 milligrams per liter
Total			84,550(±)	195(±)		

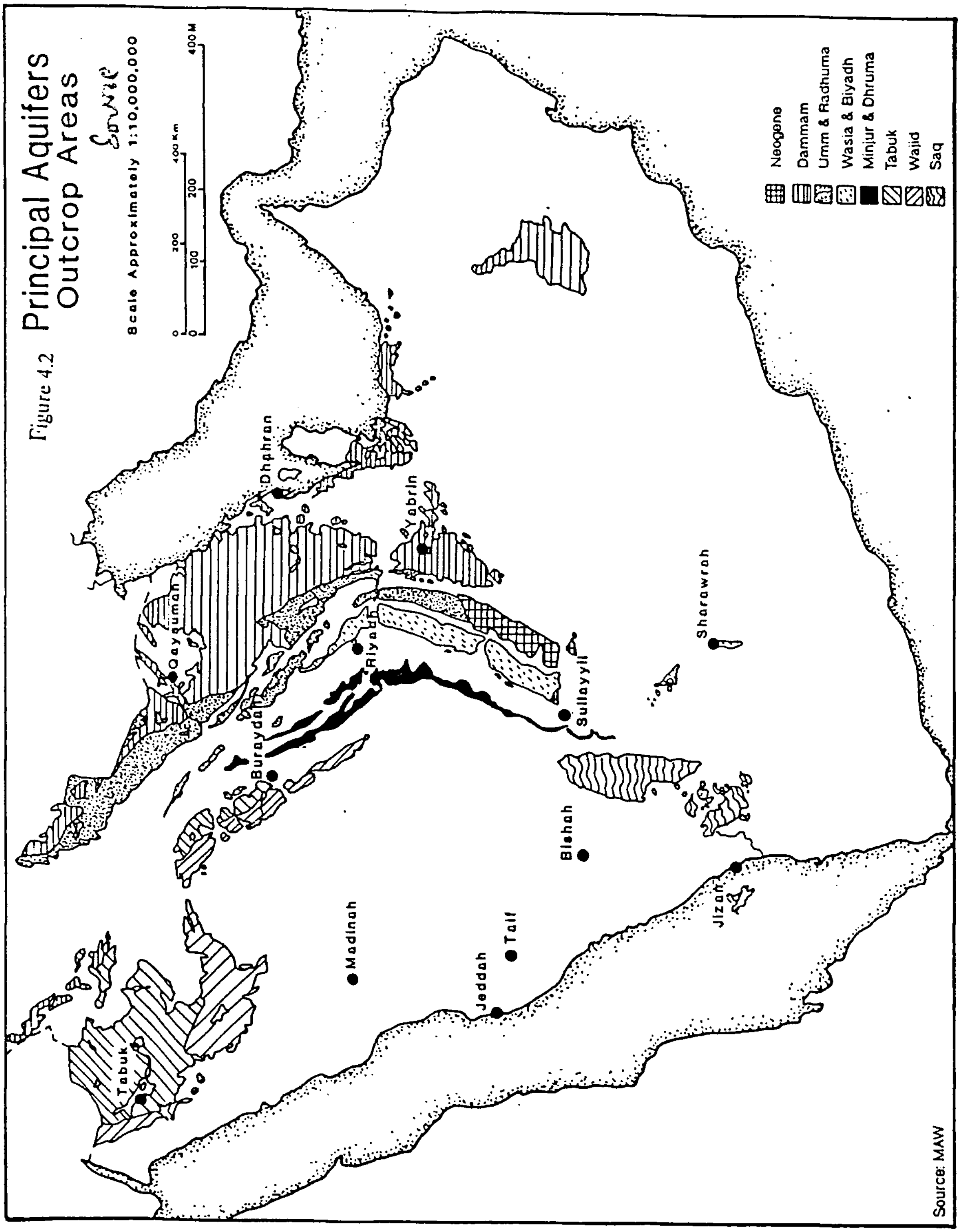


Figure 4.2 Principal Aquifers Outcrop Areas

central region and store 142 mcm. The Umm-er-Radumu, and Dammam Aquifers have major porosity and permeability variations. They yield large supplies of potable water to wells in much of eastern Saudi Arabia and store 70,500 mcm (MAW).

The aquifer is directly comparable to a surface reservoir, but the efficient management of the groundwater reservoir is more complicated than that of the surface reservoir. Apart from the need to define the boundaries of the aquifer, knowledge is required of the storage capacity of the rocks, the variation in areal and vertical permeability, the sources of inflow to the aquifer, the position and relative importance of the various outlets, and the effect of groundwater development on flows from these outlets. Saudi Arabia, where groundwater has been the main source of water for decades, considerable emphasis must be placed on assessing the storage capacity of the aquifer and optimising it.

During the Third Development Plan 1980-1985 (1400h-1495h) period such extraction rose from 1154 mcm/year in 1980 to 6480 mcm/year in 1985. Obviously, the resource volume did not change much, but its use, or depletion rate, did. The Fourth Development Plan contains relevant information. Although many values are not substantiated, there does not appear to be a reason not to accept the overall volumetric proven storage estimate of 337,500 mcm. The Fourth Development Plan 1985-1990 (1405h-1410h) the period annual withdrawals from deep groundwater to exceed 15,000 mcm before 2010 and accumulated withdrawals will then approach 300,000 mcm of a resource which now has proven reserves of 337,500 mcm.

The eight main aquifers are: Dammam, Um er Radhuma, Wasia, Biyadh, Minjur, Saq, Wajid, Neogen and Tabuk. Their principal features are detailed below.

Table 4.2: *Non-renewable water resources*

Principal Aquifer	Proven Reserves
Wasia Biyadh	89,000
Wajid	69,000
Um er Radhuma	65,000
Minjur Dhurma	53,000
Saq	49,000
Tabuk	5,000
Dammam	5,500
Total	335,500

The sedimentary formations overlying the Basement Complex form the major outcrops (Chapter 2). 30 formations ranging in age from Cambrian to Recent, have been identified and these attain a thickness of more than 5000m (MAW). Vast volumes of groundwater are stored in these rocks with sandstones, limestones, and dolomites forming the major aquifers, though, up until the present time, attention has been concentrated largely on the development of the sandstone aquifers because f the relatively high quality of their water. There are two different types of aquifers, principal aquifers and local aquifers (alluvial aquifers). As the water travels east in a downward trend, the volume and the salinity gradually increases as it approaches the Arabian Gulf. Most of the water from these aquifers from 7,000ppm to 35,000ppm (Al-Khatib, 1980). Water treatment plants are necessary to reduce the salinity to about 500ppm which is a level suitable for human use.

In recent times, groundwater recharge has been less than its discharge because of the low annual precipitation in the country (see Chapter 2, Climate). This has led to a decline of the water level in some aquifers.However, the main sedimentary formations that store water in Saudi Arabia are:

1. The Saq

The Saq is a sandstone formation of good, medium-sized grains. The thickness of this formation ranges between 300 and 600 metres, thinning southwards until it disappears. It extends to approximately 1,500 km in length and 250 kms in width.

The Saq formation rocks consist of medium-grained to course-grained sandstone but locally contain fine-grained material. The rock type is poorly to well sorted quartz. The sandstone is normally cross-bedded and devoid of shale. It is predominantly buff to grey or white, but varies locally to mustard yellow or pale brick red. The Saq sandstone equivalents are generally reddish brown massive cross-bedded sandstones. The rock of the Saq sandstone is believed to be gently folded over the Hail in the basement complex, the axis of which runs west from Hail into Jordan. The rocks may be faulted in the Tawil and Buraydah areas.

Studies completed in 1986 showed that the aquifer yielded water to wells throughout the Tabuk and Qasim areas except in a narrow strip where it is unsaturated. The Saq sandstone is probably water-bearing but occurred there only at great depth. It was found at depth of 2,784 m in the southern part of Wadi Sirhan near Khashmal Adhara. The flows diminished in force and magnitude westward towards the aquifer outcrop until they ceased entirely and pumping was required.

MAW estimates indicate that about 290 mcm has been withdrawn from the aquifer. The available data indicates that withdrawal could probably be increased to 315 mcm without seriously affecting groundwater storage, calculated at 65,000 mcm of proven reserves.

The Saq formation is a productive aquifer whose piezometric surface (under groundwater level) is very near to ground level in many areas. In some areas, the aquifer is free flowing (artesian). The groundwater occurs under the full range of conditions. It occurs in shallow unconfined alluvium and has to be pumped to the surface, as well as under high pressure artesian conditions in the aquifer where it lie at great depth below the Asyah region. In the areas the aquifer is a major source of usable groundwater. In the south, along the outcrop area west of Khuff, depth to water level in wells is about between 150m to 25m. Water is 50m deep at Tiraq further to the north and flows to the surface at Ash Sharqiyah in the Naqa region east of Hail. Eastward from the outcrop, the land surface drops off in elevation more rapidly than the piezometric surface and wells tapping the Saq will flow under artesian heads to the east.

Its hydrological characteristics are considered to be good, and water storage potentialities are considerable. As much as 315 mcm could be extracted without any significant effect on its water capabilities. Al Qassim and Tabuk regions depend heavily on this formation for agricultural and domestic water use. The water quality is excellent and the TDS range is between 450 and 800 ppm.

2. Wajid Aquifer

The Wajid sandstone is predominantly a fine- to course-grained sandstone. The rocks are generally homogeneous, very porous, poorly cemented and interbedded with shale horizons. Large planar crossbedding is displayed throughout the sandstone horizons. In different parts of the section the rock varies from white to yellow to grey-green with many red and purple haematitic bands. The outcrop forms a sloping rock surface which is partly covered by a veneer of alluvium. Its isolated hills and masses rise up to 150 m above the plain.

This aquifer is considered to possess geological features similar to the Saq formation. The thickness of this formation is 950 metres and occurs in the southwestern regions of Saudi Arabia. Its length is 3,000 km and its width is 250 km.

Hydraulic information in the Wajid aquifer is limited to the Wadi Dawasir area where the aquifer was first developed in 1966. Groundwater flows from the recharge area in the southern part of the Wajid sandstone which is the extent of the natural discharge areas in the northeast, where groundwater from the Wajid aquifer seeps into the alluvium of Wadi Dawasir. Studies completed by MAW in 1969 showed that wells flowed above the land surface at an average rate of 0.050 mcm/s in many eastern parts of this area.

The discharge from pumped wells in 1987 was estimated to be 250 mcm/year, an increase of 40 mcm/year over the 1969 estimate. The annual recharge to the aquifer, which was estimated about 114 mcm/year, was extremely small particularly in relation to the amount of stored water (MAW). The amount of water storage was shown to be substantial with proven storage of as much as 30,000 mcm. Even though storage in the Wajid aquifer was determined to be considerable, much of the year it lies at great depth.

It may be assumed that the covers an area of at least 53,000km^2. The quantity of water stored in the aquifer has been estimated to be of the order of several hundred billion cubic metres of which about 100,000mcm are stored in the unconfined part of the aquifer. The water temperature of the aquifer varies from 29°C at a depth of 15m below ground surface to 54°C at a depth of 1.116m. Artificial discharge from the Wajid aquifer is limited at present to Khammesin in Wadi Dawasir area. An estimated 10mcm/y is extracted for irrigation from pumped or free flowing wells completed in both the unconfined and artesian part of the aquifer. The hydrological situation of the Wajid Aquifer is very complex. It is tentatively estimated that there are at least 100,000mcm of water stored in the unconfined part of the aquifer.

Water pressure may reach as high as 90 metres above ground level in the wells. Water quality ranges between 400 and 800 ppm TDS and average discharge is 800 mcm/minute. Wadi Dawasir depends heavily on this aquifer for agricultural purposes, and domestic use..

3. Tabuk Aquifer

The Tabuk formation is a marine to continental sequence of cross- bedded sandstone shale, siltstone, and complexly interbedded sandstone and shale. Thickness and texture show great variation throughout the outcrop area. Colour varies from white to light purple, buff, brown and brick red.

Three sandstone units are present within the formation each corresponding to a sandy facies: the Upper Tabuk, also called the Tawil Sandstone; Middle Tabuk; and Lower Tabuk. The sandstone members are separated from each other by a shale member designated the Qusaiba, Raan and Manadir in the sequence from top to bottom. The upper sandstone is present only north of the Qasim area, but the middle and lower sandstones are present throughout the extent of the Qasim area, becoming truncated in the south. This formation stretches in a parallel pattern but overlies the Saq formation.

Until the early 1980s, groundwater development in the Tabuk aquifer was generally limited to the Tabuk-Juf-Sakaka and Buraydah areas. Groundwater recharge and other properties were difficult to determine because of the lack of data. Storage seemed likely to exceed 7,000 mcm and withdrawal was probably between 31 and 38 mcm/year at that time (Noury, 1984).

The aquifer yields good quality water, sometimes under strong water pressure to the extent that it flows in underground streams. Generally the Tabuk sandstones are not as permeable as the Saq sandstones. This formation could be subdivided according to geological age to four main members, two of which are sandstones and the other two are of shale formation. The sandstone members, namely the long member and

Tabuk member, are richer in water quality and quantity. Water discharge of the long member in some wells reaches 2,100 mcm/minute. The Tabuk member is noticeable for a distance of 900 km in length and 150 km in width southeast of Tabuk city.

The Tabuk formation contains several sandstone units which yield good quality water, sometimes under sufficient hed to flow. It is not as permeable as the Saq sandstone, and yields are less but adequate for many purposes. The Tabuk region has an adequate supply for development but it will be necessary to continually observe the mutual interference between wells. Caution should be observed, for additional discharges from the Tabuk formation will cause declines in head of existing flowing wells with a consequent reduction in free flow. However, new withdrawals, if limited to the underlying Ram and Umm Sahm, will prolong the life of the free- flowing area in the Tabuk formation which at present forms the major producing zone. In the Al-Ula region, the water supply is apparently fully exploited and additional developments would have to depend on improved irrigation efficiency or the importation of water.

The quality of its water is good for agricultural and human use with TDS not more than 800ppm. The piezometric surface is close to ground level and in some areas it is free flowing (MAW).

4. Minjur Aquifer

The Minjur sandstone, which is primarily of continental origin is a massively im-bedded, coarse to very coarse quartzitic sandstone with thin layers of limestone, shale, conglomerate and gypsum. A zone of shales and mudstones separate the formation into an upper and lower sandstone horizon. Where it outcrops in wadis, it is white or light grey, weathering to tan and red, or yellow because of oxidised iron. It consists of detritial sand and coarse, consolidated sandstone that forms 60 to 70% of the total thickness. The remaining sections consist of thin layers of hard brown and grey limestone with shale and gypsum.

As previously indicated, the formation includes some beds of shale and limestone which in some areas form 50% or more of total thickness. This is the exact condition of Minjur formation beneath Riyadh, where only 40% is water bearing sandstone, and the rest is shale.

Water quality of this aquifer is acceptable, with TDS reaching 1,200ppm, the quality deteriorates as it moves eastwards.

The depth of the water table differs from place to place, depending on the altitude of the earth's surface. That is, the water depth is the difference between the piezometric level and the ground altitude. As the ground altitude above sea level increases, the deeper is the water level. As a result, the water level is from 118 to 180 m in central Saudi Arabia, and in another area, the ground altitude is below 540-600 m. The Minjur Aquifer is the largest water reservoir in the central region, the estimated volume of stored water being approximately 750 billion m^3 (MAW). Water quality varies considerably, with salinity increasing both with depth and eastwards from the outcrop.

The Minjur Aquifer was generally developed by the early 1980s, and was by then the major source of Riyadh's water supply. Water levels in the Minjur Aquifer ranged from as much as 200 m below land surface in the Riyadh area to surface flow in the Kharj area, where flows were as much as 0.012 mcm/s.

This is the largest water reservoir of Riyadh region, spreading for a distance of 800 kms in length and 600 kms in width, with an average thickness of 300 metres. However, the drop in the water table near Riyadh, due to water extraction, has led to restrictions on water use of this formation for agricultural purposes. The Minjur aquifer is used mainly to supply Riyadh with its water requirements. Water is expensive to extract due to the depth of drilling required, which can be as deep as 1800 metres, and enormous mechanical pumping is needed, whereas in the Hayir and Kharj areas the upper and lower Minjur Aquifer is essentially artesian.

It is the largest reservoir supply to Riyadh City. Its sandstone is estimated to contain 460,000mcm of sufficiently good quality water for general use. A 100m fall in the level of the water table would correspond to an extraction of 45,000mcm, that is, 14m^3/sec for a period of 100 years (MAW). However, less than 20mcm of water were extracted, roughly 7% of the total water resources exploited to supply Riyadh City and the surrounding area. The water of Minjur Aquifer is expensive to develop, due to the great depth at which it is tapped at Riyadh (1200 to 1500m), and the high cost of pumping.

There has also been a 45m fall in the level of the water table due to mining of Riyadh.

5. Biyadh Aquifer

The Biyadh Sandstone is a lightly coloured, crossbedded quartzose sandstone interbedded with shale. Marl, sandstone and dolomite are also found in the lower unit. The upper unit is a course-grained, crossbedded quartz sandstone, with quartz pebbles. The sandstone grades to shales and shaley limestone near the Arabian Gulf. The characteristics of the landscape of the weathered Biyadh Sandstone is gently-rolling white gravel covered plains between numerous small dark coloured hills.

The sandstones of the Biyadh Formation outcrop from the Wadi Dawasir in the south to the Wadi Atj in the north, a distance of nearly 650 km. The rock of the aquifer underlies an area of about 800,000 km^2. The Biyadh Formation gently slopes to the southeast, the depth of the top of the formation ranging from the land surface of the Arabian Gulf. Biyadh sandstone is about 425 m thick at the outcrop and thins eastwards to 100 m near the Arabian Gulf.

The Biyadh Aquifer is one of the most prolific aquifer systems in Saudi Arabia. The recharge to the system which was estimated in 1967 to be 480 mcm/year, is derived from run-off from Jabal Tuwayq and under flow from alluvium in the wadis. Large volumes of water are estimated to be 8,000 years old at the outcrop near Kharj and 16,000 years in the Khurais area.

The Biyadh Aquifer is tapped by wells mainly in the Wadi Nisah, and the Khurais, Aflaj, and Kharj areas. In the Aflaj Plain, the Biyadh Aquifer and the alluvial deposits constitute an upper shallow supply of groundwater.

The quality of water from Biyadh had been determined to be generally good near the outcrop but to deteriorate as it moves downslope. The dissolved solids reading was very high: 600,000 mcm in the northeast and along the crests of the anticlinal structures. The water tended to be a calcium sulphate type. As the mineralisation increased, sodium and chloride became the dominant ions in the aquifer.

The aquifer occurs in the eastern part of the Riyadh region and is of sandstone formation. Its thickness is 600 metres and its noticeable spread is 600 kms. Its hydrological and water quality are moderate, but deteriorate eastwards.

The Biyadh formation east of Riyadh also stores a large quantity of water estimated to amount to several thousand million cubic metres. This aquifer is still little used. A general fall of 10m in the free surface level of the aquifer would correspond to an extraction of about 30,000mcm, or a flow of $10m^3$/sec for 100 years (MAW). In the upper layers, the quality of water is good but it deteriorates with depth going east. As in the case at Minjur, the water resources at this aquifer are expensive to develop because of the great depth.

The Biyadh's water is of fair to poor quality. The piezometric surface is generally 250m below ground level. Riyadh depends on this aquifer for its additional water needs.

6. Wasia Aquifer

The Wasia Formation rocks are composed of a relatively thin sandstone and shale with lenticular beds of carbonate. At places, the lower unit is conspicuously cross-bedded and the upper unit is massively bedded and weathers to heavy ledges. The formation is 1450 km long and 800 km wide, and extends inside the borders of Kuwait, Iraq and Bahrain.

The Wasia Formation consists mostly of permeable unindurated sandstone and shale of continental origin in the south, and probably marine in the central and northern areas. In the north, the Sakakah Formation, sandstone, siltstone and shale are the principal rock types.

The thickness of the aquifer increases from south to north in the outcrop area. It is 30 m thick at Wadi al Dawasir in the south, 100 m east of Al Majma'ah in the centre, and about 285 m in Sakakah in the north. The Wasia Formation, like all sedimentary formations of central Arabia, has a monoclinal structure, dipping evenly eastwards, maintaining its water bearing characteristics at least as far east as the Gulf. Water quality of Wasia varies considerably from one place to another with a general salinity increase eastward from the outcrop.

The Wasia aquifer is confined where it is overlain by the Aruma Formation, and is water-bearing as far east as Bahrain. It is the most important Cretaceous sand aquifer, and is a significant water source for Riyadh, which depends on it heavily, because of its excellent hydrological properties. Whilst it is assumed that the aquifer holds large quantities of water, especially west and south of the Ghawwar structure, development of the aquifer in eastern KSA was estimated to be very costly due to its considerable depth below the land surface: 4,850 m at Haradh. This sandstone and shale formation runs east of Riyadh region. The piezometeric surface in many wells is between 230 to 300 metres below ground surface.

The Wasia aquifer is among the richest water reservoirs in Saudi Arabia. The annual recharge is estimated at 8 to 9m^3/sec, a mean value over 30 years using Riyadh-Dhahran rainfall sequences. Recharge rates stand at reasonable values of 2m^3/sec, up to 30m^3/sec. The salinity of Wasia water eastward increases rapidly to become saline in the coastal belt. Further withdrawal would affect piezometry on a wide regional scale, vertical interaction between Wasia withdrawal and the upper reservoirs would result in negligible recharge to Al-Hassa springs.

In general, this aquifer contains good quality water but, like the Minjur water, the quality deteriorates as it moves eastward. The average depth of the water is 230m below the surface. The Wasia Aquifer supplies Riyadh with its additional water needs.

7. Umm er Radhuma Aquifer

This aquifer consists of a series of light-coloured dense limestones, dolomitic limestones and dolomites, laid down in shallow seas. Marls and shales are also found in the upper part of the formation in the central and southern areas. In the north, significant layers of anhydrite and some chert are found in the upper part. Eastward in places, the thin anhydrite layers have been removed, which has led to solution collapse structures. The upper part of the formation is more porous than the lower as a result of the weathering out of a lattice of poorly cemented dolomite crystals and the general enlargement of joint surfaces into fissures.

The formation has an average thickness of 240 metres. The aquifer occurs in the Eastern province of Saudi Arabia, extends for 1000 kms, and is noticeable in Iraq, Kuwait and Bahrain.

The Umm er Radhuma Aquifer, which consists of the Umm er Rhaduma Formation is a single, thick hydraulic unit and is water-bearing throughout much of the eastern region and Rub-al-Khali.

The recharge to the aquifer is by direct infiltration of seasonal rainfall over the outcrop and by run-off from wadis. As with other aquifers in KSA, the recharge is very limited. Of the 60 mm/year average rainfall that falls on the outcrop in the eastern region an estimated 4 to 8 mcm infiltrates into the aquifer. Groundwater was found to flow to the east and north east from the outcrop. The yields of wells ranged from 0.04 to 0.32 mcm/s in most areas, and locally as much as 0.95 mcm/s.

Water potentialities of the Um er Radhuma aquifer are considered to be of significant quantity, and possess good hydrological characteristics.

The formation is a most important aquifer of the Tertiary, and potentially the most plentiful source of water for domestic and agricultural use. The most productive zone is in the upper part of the formation, constituted mainly of poorly cemented dolomite crystals. The salinity increases from less than 1,000 to over 6,000ppm from west to east. An anomaly exists in the southern central part of the area, where the tongue of good quality water reaches as far as the Dammam Area. This is free flowing over a wide area and its transmissibility was found to be high near Dammam in the Wadi Al-Miyah zone and around Harad. The high potential production of the aquifer, which at present is free flowing over vast areas, and which has been shown to have very high transmissivity values in the wells. These features justified the assumption that the aquifer could be intensely exploited, with extraction of the order of several hundred mcm/year.

The water level at the wells drilled in the eastern province reaches up to 50 metres above ground level. Such wells produce by themselves $150m^3$/min, which reflects high permeability. Whilst water quality is 1800 ppm TDS, it is being used successfully in agriculture in Wadi Miyah eastern province and in the Harad Project.

The water quality of this formation ranges from fair to poor with TDS. Therefore, the primary use of this water is for agriculture. The Umm- er-Radhuma formation is highly productive artesian in some areas.

8. Dammam Aquifer

The rocks of the Dammam Formation are characteristically light- coloured limestones, marls and shales. The carbonates often have interbedded layers of fine clastic material. The Dammam Aquifer is composed of two carbonate members, the Khubar and Alat limestones. The Midra, Saila and Alreolina members are shale beds with low permeability. This formation, which occurs in the Eastern Province of Saudi Arabia, consists of white limestone, brown dolomite, and to a smaller extent marl and clay. It has a average thickness of 35 metres, reducing to 9 metres in places. Average depths below the land surface vary from 80 to 120 metres.

Shale of the formation overlies conformably on soft, chalky limestone or calcarenite of the Rus Formation which is a low grade aquifer at a few places. Although the aquifer is thin compared with the other principal aquifers, it has been tapped by thousands of wells because of the shallow depth to the water and reasonably good permeabilities of the rocks. The Dammam Aquifer discharges into springs in the Qatif area, submarine springs off the coast, and upward into the overlying Neogene Aquifer.

The specific conductance of 870 water quality samples collected ranged from 1,180 to 26,200 micromhos. Dissolved solid concentrations of less than 10,000 milligrams/m^3 were found at and near the outcrop and in the Haradh area, allowing the water to be used for small-scale agriculture in Qatif, Khubar and Dammam, and averages 1300 ppm TDS. Concentrations of calcium increased as mineralisation increases. Water capabilities are moderate and discharge does not exceed 20 m^3/min in most wells.

9. Neogene Aquifer

The Neogene Aquifer consists of three subformations: the Hadrukh, the Al Ladam and Hofuf formations, which are sandy limestone, marls, chalky limestones and to a smaller extent sandstones and clay, with a thickness of 300 metres. The Hadrukh Formation consists of marls. The colour varies but mainly shades of green or grey. The Dam Formation consists of red, green, and olive clay, with interbedded pink, white and grey marl, chalky limestone, and coquina. The Hofuf formation is a conglomerate of sandstone, sandy limestone, sandy marl and sandy shale. The upper beds of limestone cap the coastal land and Summan Plateau exposures. Inland, the continental rocks are an undifferentiated single unit of sandstone, marl and limestone. The Kharj Formation is made up of scattered deposits of lacustrine limestone with associated gypsum beds and gravel.

The major areas of development in the Neogene Aquifer are located in the Hassa oasis, and along the western edge of the Qatif oasis. Some of the water which feeds the flowing wells and flowing springs probably issues from the Dammam Aquifer through the Neogene Aquifer. Of the 162 springs in the Hassa oasis, that with the largest flow had a measured rate of 1.8 m^3/sec, however, most flows were much less. As with the physical properties of the aquifer, the quality of the water, ranging in dissolved solid concentrations from a few hundred to over 100,000 milligrams/m^3.

Water from the aquifer has been shown to be a sodium chloride type. Some of the samples have contained high concentrations of nitrate.

The Neogene Aquifer is an important source of water locally in the Eastern Province near the Arabian Gulf. The hydraulic properties of the aquifer have been found to vary considerably because of the rapid lateral and vertical changes in the lithology. As a result of these rapid variations, groundwater occurs irregularly in the aquifer.

The aquifer has a high potential for development in the Hufuf zone where all the other aquifers have somewhat low transmissibility values. Almost all the water abstracted on the Al-Hassa Oasis comes from this aquifer. Groundwater quality is generally bound up with groundwater movement. The best quality water is found where permeability, and hence flow rates, are high. The aquifers are separated from each other by impervious formations. However, separation is not always continuous because of fracturing, formation thinning or facies variation. Hence leakage between one aquifer and another occurs in some zones and the deeper seated aquifers leak to those lying above, such as that of Al-Hassa where the Neogene carries hot waters coming from the underlying Umm er Radhuma, and probably Wasia formation.

Water and hydrological characteristics are moderate, and water is used for agriculture in the Al Hassa region.

The above mentioned formation presents two main problems:

- Most of the water stored in them is brackish and requires treatment before it is suitable for human use.
- They are subject to over-extraction because of the very low natural recharge.

4.3.1 Summary

In Saudi Arabia, as shown in Figure 4.2, there are nine major confined aquifers, Wasia, Biyadh, Wajid, Umm-er-Radhuma, Minjur, Saq, Tabuk, Dammam and Neogene. Several consulting companies under the supervision of MAW conducted numerous studies throughout the country to estimate the volume of groundwater in these aquifers. A subjective assessment of proven, probable and possible reserves for the groundwater aquifers have been made as shown in Table 4.2. The proven reserve, is the groundwater amount which can be developed with a high degree of confidence given that the aquifer properties are as anticipated. The probable and possible reserve estimates are less certain than the proven reserve. Recharge of these aquifers which mainly comes of leakage from shallow alluvial aquifers and rainfall at the outcrops is in the order of 1,270mcm/y. These aquifers currently supply more than 75% of Saudi Arabia's water needs. Saudi Arabian water requirements between 1985-1995 are about 9,600-13,000mcm. This shows that withdrawals far exceeds natural recharge of these aquifers.

The hydrological and hydrogeological and the ensuing assessments of the water resources which could be exploited in various parts of the country. The most important aquifers in the areas lie in the sedimentaries extending from the Wasia formation to the Neogene.

Regionally all the aquifers show great variability in productive capacity, coefficient of permeability and total porosity, especially those composed of limestones. Fractures render the limestones heterogeneous, this is a fundamental hydrogeological characteristic. It would use that most wells tap water from horizontal solution openings which are especially well developed in zones where vertical fracturing is the most intense. Fractures and solution openings are more abundant along the crests of anticlines and within synclinal troughs than on the flanks of folds. This seems to be amply demonstrated by the wells drilled in the areas and in the syncline which flanks the Ghawar structure.

The water temperature of the aquifer can be considered normal in as much as the temperature varies with depth, being close to the normal geothermal gradient, but in other aquifers it varies from 39°C at a depth of 15m below ground surface to 54°C at a depth of 1.116m. The total dissolved solids range from 526ppm to 824ppm in the whole of the artesian areas. The groundwater flows from the deeper aquifer into Quaternary aquifers and then moves eastward at wadi under-flow.

Consequently there exists leaky artesian conditions which lead to the Biyadh-Wasia-Aruma aquifer discharging into the Umm-er- Radhuma. The Biyadh-Wasia-Aruma aquifer can be considered as a single hydraulic unit. The intercalations of clay, shale and occasional dolomite and limestone are not, in all probability, sufficiently thick or continuous to form aquicludes. As these formations are so difficult to separate, they are in fact referred to collectively by the name "Cretaceous Sand".

The aquifer systems pass by alternation into the argillaceous succession that make up their confining limits. The most important is that of the Upper Minjur which provides most of Riyadh's present water supply. The aquifer system was therefore the main subject of the Minjur survey. The results of the water supply potential of both the Minjur and Wasia Aquifers show they contain a very large quantity of water. To convey domestic water from either of the two aquifers it was necessary to make comparisons between the two, taking into consideration many elements, starting from the well fields up to the reservoirs in the city of Riyadh.

4.4 Local Aquifers of Saudi Arabia

Local aquifers are, by definition, locally important sources of water. Their water quality and yields range from poor to good. Like the principal aquifers of Saudi

Arabia, local aquifers range in their extent, geology, hydraulic character and state of development.

Whilst much of Saudi Arabia is covered by Quaternary deposits, Figure 4.3 shows that most aquifers are located in the western (and south western) regions of the country. Local aquifers are unconsolidated and of limited thickness, rarely exceeding 100 m. The average width of these aquifers is about 1 to 2 km, whereas their length can run up to 10 km.

Groundwater of the aquifers are usually used for municipal and agricultural purposes. However, the increasing water demand of the cities has restricted agricultural practices to a limited area in the upstream reaches of the aquifers. The mean annual recharge of aquifers is estimated as 900 mcm. About 80% of this recharge amount occurs in the western and south western regions.

The Jauf, Khuff and Jith aquifers yield low to moderate supplies of poor to good potable water to wells in the northern and central parts of Saudi Arabia. In some areas, the Jith is connected hydraulically to the Minur, one of the country's principal aquifers. The Khuff yields moderate to highly mineralised water to wells in the Qasim and Wadi Dawasir areas. As of 1984 its potential for development was thought to be best in its southern reach where the rocks change lithology from limestone to sandstone. The Aruma aquifer, except where it is connected hydraulically to the Wasia Aquifer, provides low yields of highly mineralised water.

The Jauf aquifer is water-bearing. Information on the aquifer's properties is limited to the area between Sakaka and the TAPline (northern Saudi Arabia). Data available in 1984 were as follows: yields were calculated to be between 0.016 and 0.024 m^3/s; specific capacities from 1.18 to 1.26 l/s/m; the top of the formation below the land surface from 1,400 to 1,200 m; depths to static water are from 22 to 148m (MAW; Noury, 1984).

In the Khuff aquifer, yields from the few wells in the northern area (Qasim area) were to range from 0.007 to 0.023 m^3/s. Only limited hydrological data were available for the aquifer except in the southern area (the Kumdah, Dawasir and Ruhayah Members). Transmissivity of the Kumdah Member was to be about 103 m^2/s or less, and estimated yields are about 0.02 m^3/s. The dissolved solids concentrations from selected wells were between 3,000 and 4,000 milligrams/l in the northern area, 2,000 and 6,000 milligrams/l in the coastal area, and 845 and 1,900 milligrams/l in the southern area (MAW; Noury, 1984).

In the Jilh aquifer, the volume of water in storage was known to be considerable due to the great thickness of the rocks. In the outcrop area west of Riyadh, yields to wells range from 0.01 to 0.018 m^3/s. In the Qasim area, however, yields were only moderate because of the low permeability. Eastern Riyadh area yields averaged 0.063 m^3/s (MAW and Al-Khatib, 1980)).

The Basalt Aquifers are significant water sources where they overlie the alluvial deposits of original drainage channels. Basalt of Tertiary and Quaternary age covers large areas of the Arabian Shield and large areas of the sedimentary rocks in the northwest locally. In the Arabian Shield, wells tap the aquifer in the Precambrian crystalline rocks, but yields are limited because of poor permeability and storage, and the low intensity and infrequency of rain.

Basalt aquifers, lava fields accompanied by numerous spatter or cinder cones and small flows or ash fields, are scattered over extensive areas of the western Saudi Arabian highlands and the coastal area of the Red Sea.

As few wells tap the basalt, data about aquifer characteristics are limited. At Hadhawdha, however, there are wells that yield high volume flows of relatively fresh water. Mineral concentration of water from the basalt aquifers was found to be generally low. The specific conductance of 45 water quality samples ranged from 400 to 7,900 micromhos, with a median value of 1,130 micromhos (MAW).

The Sakaka sandstone, of Middle Cretaceous age, is named after the town of Sakaka in northwest Saudi Arabia. Most of the hydrological information about the aquifer was gathered from wells in the outcrop area around Sakaka. Yields of wells were shown to decrease northward from 0.018 m^3/s at Sakaka to 0.001 m^3/s at the TAPline. Transmissivity at the outcrop ranged from 3 x 10^4 to 2.8 x 10^3 m^3/s and the storage coefficient from 6.7 x $10^4 m^3/y$ (MAW). The elevation of the potentiometric surface declined from the outcrop northward to such an extent that at Sulaymaniyah static water level was 200m below land surface. Water quality was limited in the area where dissolved solids concentration ranged from 400-600 mm/l. Dominant ions were shown to be sodium/calcium chloride and sulphate. Some of the water contained an unusually high concentration of magnesium.

The Aruma Formation, which is of Upper Cretaceous age, was named after Aruma northeast of Saudi Arabia. The Aruma Aquifer had been developed in only a few restricted areas because of its very low permeability. The dissolved solids concentration in the Arar and Julamid areas ranged from 1000 to 1800 mm/l (MAW). The water was rich in calcium sulphate, although at higher levels of mineralisation, sodium ions became dominant.

Alluvial deposits fill many drainage channels on the western coastal plains of Saudi Arabia. The deposits were laid down by flood waters as surface material on the wadi floors and in terraces above the wadi floors when the streams flowed at a higher elevation. Alluvial deposits are also found in old wadi valleys where the flow has followed new drainage patterns. Some of these deposits in abandoned wadis were later buried by lava flows or windborn deposits. Alluvium, carried by streams that drain to the Red Sea coast, form large fans that coalesce and grade into wadi tracts on the coastal plain. The fans are formed at the base of the Red Sea escarpment where the land slope flattens.The alluvium is made up of material which ranges in particle size from clay, silt and sand to gravel and boulders.

Streambeds filled with coarse material serve as the best water bearing deposits because of their ability to serve as a storage reservoir and to transmit water easily. The aquifers are generally unconfined but may be semi-confined or confined where silt and clay are interbedded with sand layers. Studies have shown that transmissivity generally varies from 1×10^3 to 1×10^3 m^2/s and the coefficient of storage from 1×10^3 to 1×10^5 (MAW; Noury, 1984). The higher values were found in deposits near the centre of the wadis. Yields varied greatly, from 5 l/second from dug wells with hand drawn buckets to as much as 50 l/sec from modern well-designed cased wells with pumps. The alluvial aquifers are generally long and narrow corresponding to the wadi channel and they vary greatly in thickness.

The alluvium in the wadis increase from 10 m thick in the upper reaches to as much as 100 m at the intersection with the plain. Along the Red Sea coastal area the deposits generally range from 10 to 20 m thick but locally can be much thicker. Aquifers in these deposits are mainly used for domestic and livestock supply but, locally, some are used for irrigation. The aquifers have often been tapped by galleries and wells.

The Quaternary aquifers of Saudi Arabia consist of the saturated part of the alluvial deposits in drainage ways and various plains which were formed by outwash deltas and fans. It had been determined by 1984 that the most promising of these aquifers were to be found in the alluvium of the larger wadis and in the alluvium and related deposits of the western coastal plains. Wells in these aquifers are used to supplement water supplies for irrigation and municipalities.

4.4.1 Summary

A large portion of Saudi Arabia is covered by the Quaternary deposits. However, as shown in Figure 4.3, most of the alluvial aquifers are in the western and southwestern regions of the country. These alluvial aquifers are unconsolidated and of limited thickness, rarely 100m. The average width of these aquifers is about 1 to 2km while length could run up to tens of kilometres. Groundwater of the alluvial aquifers are usual for municipal and agricultural purposes. However, increasing water demand of the cities has restricted agricultural practices to limited areas in the upstream reaches of the aquifers. The mean annual recharge of the alluvial aquifers is estimated as 900mcm. About 80% of this recharge amount occurs in the western and southwestern region.

Aquifers in the alluvium: These aquifers are those in most widespread use and they supply 75% of all the areas. They do not hold very much water and the amount of water stored in them has diminished considerably. No increase in tapping can be envisaged in the future and it will be necessary to reduce pumping in most cases, with the possible exception of Hawtah, Hillah, and Hilwah regions in order to regulate storage.

The Khobar aquifer has very good development potential in the coastal belt where it is free flowing over vast tracts, and also in the Wadi Al-Miyah zone. In assessing the groundwater development potential in areas, account must be taken of the aquifer systems which are interconnected hydraulically, as in some cases extraction from one aquifer affects the other. Extraction of groundwater from the Alat-Khobar system

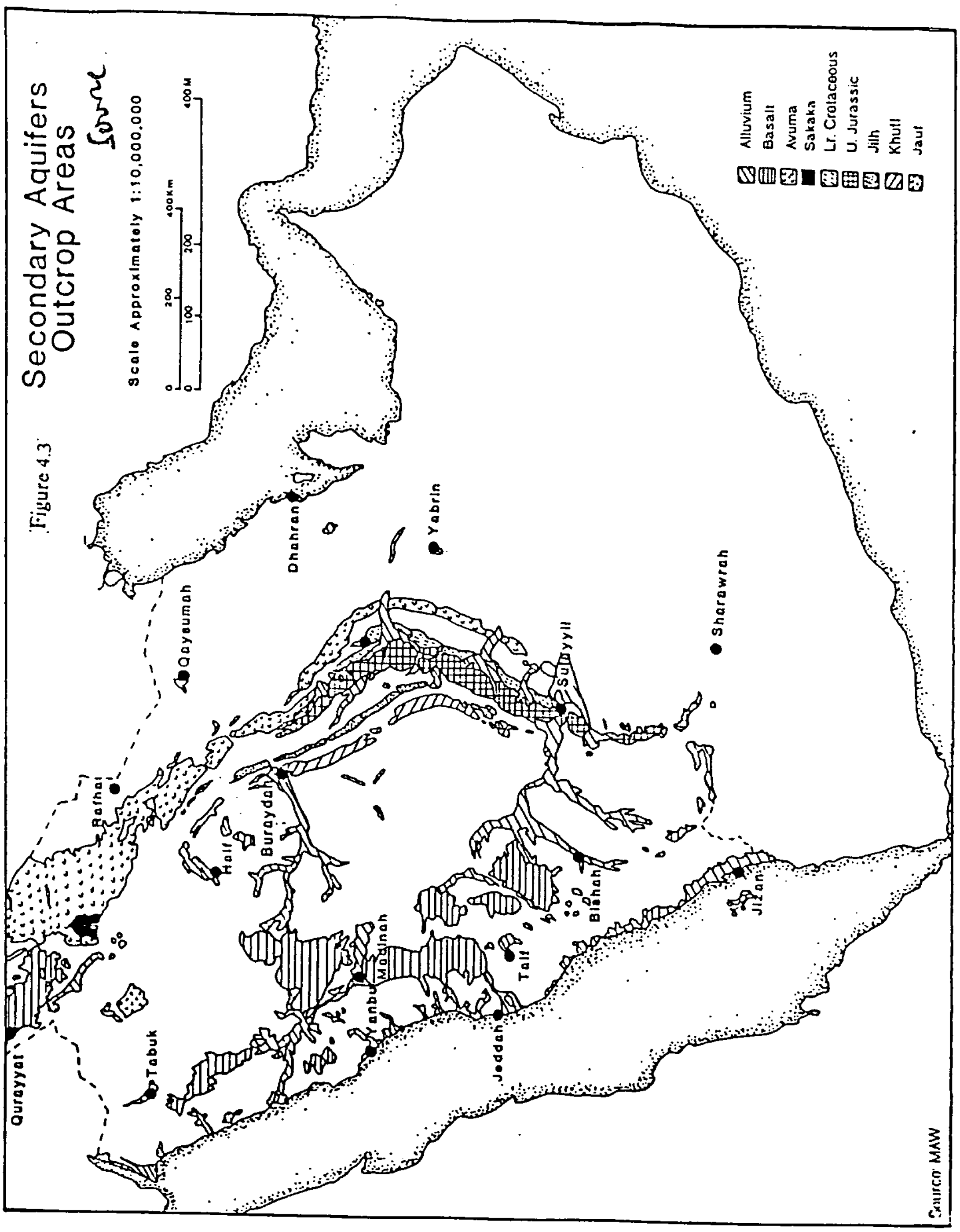


Figure 4.3
Secondary Aquifers
Outcrop Areas
Scale Approximately 1:10,000,000
0 100 200 400KM
0 200 400M
Alluvium
Basalt
Avuma
Sakaka
Lr. Cretaceous
U. Jurassic
Jilh
Khuff
Jauf
Qurayyat
Tabuk
Rafhai
Hail
Buraydah
Qaysumah
Dhahran
Yabrin
Sulayyil
Sharawrah
Madinah
Yanbu
Jeddah
Taif
Bishah
Jizan
Source MAW

should not be increased until potential productivity is known. Water abstraction from this location would aggravate the threat of future encroachment of sea water.

The alluvium aquifers consist of surface deposits of coarse sand and with minor amounts of fine grained gravel and may contain silt and clay. The water table along areas are at relatively shallow depth and the quality is poor, with dissolved solids content varying from 800ppm to over 24,000ppm.

4.5 Groundwater Movement

Movement of water from one point to another is caused by a difference in flow potential. In groundwater, the head usually consists of two components, a pressure-head and an elevation-head.

As the groundwater moves eastwards in a down-dip direction, it is often confined between aquicludes and so artesian pressures are built up. A proportion of this water eventually issues forth as submarine springs on the floor.

Increasingly, the cause of falling water-tables is excessive exploitation of groundwater. Some aquifers can sustain exploitation (their natural recharge is enough to cover natural losses plus human demands) but the recharge of some cannot replenish losses due to human extraction. Where an aquifer is unconfined, simply spreading water on the ground and delaying run off with check-dams or earthen ridges may be all that is needed. Confined aquifers must usually be recharged by forcing water down boreholes or into suitable outcrops of the aquifers.

As regards the movement water, it should be noted that permeabilities associated with unsaturated flow are less than those for saturated flow. The lower the degree of saturation, the lower the permeability. Physically this is logical, because with a proportion of the void occupied by air, water is impeded in its passage through porous media. Permeability approaches zero near the threshold saturation point, indicating no flow. At this lower limit, water is held primarily by capillary forces and is distributed in individual concentrations in the small pore spaces.

Since groundwater is present in several distinct settings, its quantity and motion are subject to different hydraulic parameters.

The groundwater table movement is therefore very much lower than the average carried by the wadis ($32x10^6$m/annum) (MAW). This appears to bear out the observations that can be made on the surface.

The following factors influence groundwater flow in Saudi Arabia (MAW and Noury, 1984):

1. The presence of water-bearing lithologies of alternating sequences of highly permeable Quaternary alluvia, underlain by less permeable Tertiary conglomerates and clayey formations. As a result of these lithological variations, porosities are also expected to be different and, therefore, groundwater velocities.
2. Topography and subsurface geology dip toward the east, north, central and south, but more towards the latter. This inclination in the land has influenced surface flow, as is evident in the major flow channels of wadis.
3. The occurrence of wedge-like highly permeable buried alluvial channels that may have been old flowing ancient wadis that served as drainage lines during the sea level changes that have occurred since the later Pliocene. Such highly permeable buried wadi channels influence greatly the diffusion of recharge water from the catchment areas by vertical and lateral seepage, and provide wedges of stronger groundwater head and therefore faster subsurface flow. The most important of such buried alluvial channels is the ones which are located in the main wellfields.

On the regional scale, groundwater movement in Saudi Arabia, is controlled by the so-called sabkha line, which demarcates the low- lying areas. The central and west are the recharge areas to the east and south. The deep formation aquifer system of country is thickest and deepest in north and central areas. The upgradient (recharge) parts of the system are in west-central. The regional groundwater flow is, therefore, in deep formations towards the lowest part of Saudi Arabia.

The quality of water in the zone of overfill reflects that of the water which has percolated to the water table and the subsequent reactions between water and rock which occur.

4.6 Groundwater Quality

Groundwater quality reflects the geology of an aquifer because the water tends to dissolve minerals with which it comes into contact. The major ions dissolved in groundwater are sodium, calcium, magnesium, bicarbonate, chloride and sulphate.

Rainwater may leach light salts which have accumulated at the surface into the groundwater. These salts may be concentrated in the groundwater as a result of evaporation and transpiration. Water loss by transpiration depends on the type and density of the vegetative cover, which is governed by climate and soil type.

In any evaluation of groundwater resources the quality of the water is of almost equal importance to the quantity available. Furthermore, details appertaining to groundwater quality may throw some light on such factors as the interconnection between surface water and aquifers, groundwater movement and storage.

Once water moves into the ground, it has a relatively stable environment in which the characteristics that determine its quality tend to change very slowly unless man-made pollution speeds up the process. Thus the quality of groundwater, although generally more mineralised, is much more constant than that of surface water, which changes continuously in a changing environment.

More than 15,000 groundwater samples have been collected from more than 10,000 wells throughout the country. The samples represent water from 37 single aquifers. They also include 55 mixed samples that represent water from combined or multi-layer aquifers. About two-thirds of the samples were analysed for the major cations and anions, and one-third for specific conductance and temperature only (MAW; Noury, 1984).

Deterioration of water quality results from a wide variety of causes. The excessive use of groundwater and the steady decline of water levels lead to the intrusion of seawater into aquifers, increasing the TDS content and making water too saline for direct use (El-Khatib, 1980).

The water extracted from another adjacent aquifer and returned to the aquifer itself, as a result of surplus irrigation, seems to be more mineralised than the recently infiltrated water. Such water is common in and near the cultivated areas. Another kind of water with relatively high mineralisation seems to be found when the water table in the alluvial aquifer is very low. Such water moves to the aquifer from the surrounding limestone formations according to their slope, or through lateral sub-surface inflow (MAW).

Water quality data most commonly used are expressed as parts per million (ppm), or as the weight of dissolved solids in water, in mg/l. The type and concentration of dissolved salts depends on the environment, movement, and sources of the ground-water. Greater concentrations of dissolved constituents are expected in groundwater than in surface water because of the greater exposure to soluble materials contained in geologic strata. The most common soluble anion in groundwater is bicarbonate which is derived from carbon dioxide released by organic decomposition in the soil. Other common elements in groundwater include anions such as carbonates, chlorides, and sulphates, and cations such as sodium, magnesium, calcium and potassium. The total dissolved solids (TDS) concentrations in fresh water normally range from 0 to 1,000ppm. Some areas' wells exhibit a range of 256-362ppm, such as in the northern and central areas of Saudi Arabia, and in other areas TDS ranges from 460 to 598ppm. The hardness of water (the sum of calcium and magnesium ions, expressed in ppm) is another important factor in judging the suitability of water for municipal, industrial, and domestic supply. The hardness of water from a well field which ranges from 53 to 76ppm, is considered soft to moderately hard, and from another well field hardness ranges from 80 to 109ppm, which is considered moderately hard, such as in Tihama Asir and eastern areas.

Groundwater quality is threatened by percolation of concentrated waste water. Leakages from domestic sewage and sanitary dumps and landfills increase the concentration of nitrates in the groundwater which adversely affects the chemical character of water. In many areas of the country, cesspools or septic tanks are used to dispose of waste water. In many instances, tanks may not have been constructed and maintained properly resulting in overflows and contamination of nearby wells. Studies in several areas around Riyadh have shown groundwater to be contaminated by waste water.

4.7 Groundwater and Well Hydraulics

The extensive development of groundwater supplies by means of pumping wells makes it important that practical solutions to well flow problems are obtained. In order to achieve this, type of flow and boundary conditions must be determined. Although such solutions often only approximate field conditions, they provide valuable insight into the intricacies of groundwater flow.

No sudden depletion of aquifers has occurred, nor is it expected to occur. Depletion is a gradual process indicated by two common and interrelated symptoms, decline of water levels and decrease in well yields. In many areas, the water table of deep aquifers has been steadily and rapidly declining, resulting in decreased water withdrawals and increased pumping. In some areas, wells have been abandoned, and in other areas, wells have had to be deepened and pumps had to be lowered to reach lower water levels, in particularly hot regions, such as in central and northern Saudi Arabia.

The groundwater investigation reviewed available data regarding existing wells. Wells are either drilled or dug. Land owners dig private wells for their fields. Other wells are governmental, and drilled for urban use. Installation of pumping machinery is necessary to lift the water to the surface from a depth usually ranging between 10 m to 30 m, but sometimes from even deeper. When a well is pumped, water is removed from the aquifers surrounding the well and the water table, depending upon the type and aquifer, is lowered. The drawdown at a given point is the distance the water level is lowered (MAW).

In Wadi Al-Dawasir area, there are a number of small oasis along the northern edge of the wadi where about 2000ha are irrigated mainly from traditional hand dug wells 5-25m deep in shallow alluvium. Also in Najran area, there are wells drilled 10-30m deep, for domestic and agricultural irrigation use.

Insufficient rainfall results in little or no recharge and leads to declining water levels in the country's aquifers. Water levels do not rise or decline uniformly throughout an aquifer when a change of storage occurs. Aquifers in the sedimentary strata of the Arabian Shelf contain substantial volumes of water in storage, whereas aquifers in the crystalline areas of Saudi Arabia generally contain lesser quantities. The water level in an aquifer fluctuates in response to changes in the volume of water stored within the aquifer in much the same manner that the water level in a surface reservoir varies with storage changes, that is, the groundwater level responds when water is taken into or released from storage. In consequence, the groundwater level tends to rise when recharge exceeds discharge and tends to decline when discharge exceeds recharge. A further lowering of the water levels results from water withdrawals from pumping wells. Minor changes in water levels may be due to seasonal tidal and barometric fluctuations.

The installation by the MAW of a countrywide network of observation wells to monitor groundwater levels is now underway. Over the next twenty years, about 300 such observation wells will be brought into service. The Al-Jauf-Sakakah region has developed enough groundwater for current needs. Tests of wells drilled 250m deep, in each of the communities, indicates that adequate supplies are also available for additional development.

Hydrographs of observation wells near the outcrops of the aquifers in central and northern country show seasonal rises in water levels during the winter when the aquifers are recharged by annual rains. However, because of their lower permeabilities and highly mineralised water, the sandstone aquifers are not important sources of potable water throughout the country.

Limestone aquifers of Cenozoic age yield larger quantities of water to wells in areas where solution channels and caverns which possess good storage and water bearing properties have developed. Whilst these aquifers are important, neither water storage nor yields are high. The aquifers are located throughout the country and are generally minor sources of water. Some, however, are hydraulically connected with underlying aquifers and provide large quantities of water to wells.

The water stored drains off when the levels in adjacent and more permeable aquifers fall due to pumping. For example, water stored in the Tuwayq Mountain limestones is tapped via alluvial aquifers in the wadis, and similarly water in limestone aquifers upstream of the Al-Kharj plain drains into the sandy alluvial aquifer in the middle of the plain. Supplies from water bearing limestones are available for direct use only where the rock is weathered and has turned to Karst, as in the eastern lowlands of Wadi As Sulaiy, Al-Kharj and Aflaj.

4.7.1 Drilling of Wells

Exploratory wells varying in depth of sand, silt, gravel and boulder. The hydrogeological evaluation of the geoelectric survey indicated that:

1. The main groundwater body is strongly saline in Wadi Al- Miyah.
2. The saline water is overlain by a body of fresh water in Wadi as Sirhan.
3. The fresh water reservoir is a subterranean channel system similar to the present drainage system in Wadi Bishah.
4. The maximum thickness of the fresh water body is more than 100m and has been located in Wadi Baysh and Wadi Sabya.

Groundwater quality has been classified into three groups:

1. Bicarbonate water which can be found in the upper courses of the wadis.
2. Chloride water as the dominant anion in samples of all wells.
3. Sulphate water mainly in the middle course of Wadi Baysh in the upstream of Wadi Sabya and South Samtah.

Pump irrigated farming has started to develop in recent years and is expanding rapidly. The farmers are concentrated in large settlements and grow mainly vegetables.

Most of the supplies that have to be raised from underground are tapped by wells. The wells may range upwards in diameter from 100 cm and are bored by well drilling machines. Hand dug wells may be excavated when machines are not available and when the water table is within reasonable distance of ground level.

The downward trend of water levels in aquifers near well fields shows the effect of heavy withdrawals. The hydrograph of wells in the Wasia Aquifer shows that the water level has declined from 131 m above sea level to 125 m, and in other aquifers such as the Saq Aquifer from about 22 to 12.8 m. The average rate is 7.5 m/year in the Minjur Aquifer, with levels which have declined to about 82 m at the well field (MAW).

Many towns, and most areas of dense settlement, are in places where groundwater can be reached by hand dug wells. However, many of the wells reached only to perched water table of limited capacity fed by the rains of the current year so that water supply was a variable and could be precarious in a severe dry season. To small and isolated villages, failure of its wells could be disastrous and this may be an explanation for some abandoned settlements. The water demand of the use has increased enormously when it was estimated that the peak demand would increase for domestic and agricultural irrigation used consumption per capita per day, that the government is to provide water for use. The MAW is giving high priority to the drilling of wells either directly or through the letting of contracts to local and international construction companies. In 1987 MAW finished drilling 28,000 wells producing an estimated 1,723 m^3/annum in various parts of the country. The wells were drilled to different levels ranging between 60 m and 1500 m.

Major projects in the area include drilling of new wells, repair and replacement of old wells, expanded and upgraded distribution networks.

MAW signed a commercial contract with a company to operate and maintain 187 wells for five years between 1968 to 1973. MAW drilled 300 wells. Exploitation of these supplies was developed mainly between 1973 and 1980. The number of burls increased to about 2,906 wells. Table 4.3 shows that MAW drilled additional wells in various parts of the country and lists the wells drilled for different purposes during the period 1982-1986. For piped drinking water: 3142; control and test wells (to measure water levels): 1071; agricultural purposes: 290. The estimated total number of wells used for different purposes in KSA is 4554 (see Figure 4.4 and Table 4.3). The depth of a well is, in part, a function of the vertical movement of the water table as a result of water withdrawal. The greater the withdrawal, the deeper the well must be sunk, for example, the drilled wells like the one which is planned to supply the towns, such as Sabya, which reach signiifcant quantities of water 100 m underground. The wells are being pumped at a constant rate of 1500 mcm/day at an observation well 100m away. In addition, the total number of wells in different areas Saudi Arabia is around 28,863 well. The pumped water is around 1723.0 mcm/year.

Table 4.3: *Wells drilled by MAW for different purposes*

Type	1982	1983	1984	1985	1986
Tubular Drinking Wells	1473	1581	1650	1711	1751
Manual Drinking Wells	1146	1234	1295	1354	1397
Control Wells	741	747	747	748	761
Test Wells	332	337	355	355	355
Agriculture Wells	286	290	290	290	290
Total	3978	4189	4337	4458	4554

FIGURE 4.4

Well Drilling and Extraction of Water for Irrigation

4.7.2 Introduction

The well in a homogeneous aquifer of infinite extent with an initially horizontal water table. For flow to occur to the well there must be a gradient towards the well. The resulting water-table form is a cone of depression. If the decrease in water level of the well is small with respect to the total thickness of the aquifer, if the well completely penetrates the aquifer, and assuming equilibrium, a formula relating well discharge and aquifer characteristics can be derived. Although the study well have known about groundwater for levels and quality, early humans probably learned from the animals how to find water beneath a dry stream bed. A thirsty area in Central Saudi Arabia and north of it will dig a drinking hole in a stream bed in which groundwater lies just beneath the surface. The MAW developing a pastoral economy, and dig wells to supply their flocks. Even though much of the water supplies for most large cities come from surface streams and lakes, a large part of the country still depends on groundwater from wells.

4.7.3 Wells

In porous and permeable sediments such as gravelly alluvium, the yield of a well can be proportional to its depth.

Although rural areas still use hand-dug wells, especially in many less developed countries, most wells today are drilled with well-drilling machines (drilling rigs) and are cased with metal casing. Although water is lifted from dug wells in buckets or other containers in a few primitive societies, nearly all groundwater is lifted nowadays by mechanical pumps powered by either electrical or internal-combustion engines.

Many farmers are dependent on hand dug wells, which perform a satisfactory service. They can be improved by lining with concrete or metal plates. Screens may be installed to increase the yield from sands, and hygienic surrounds can be provided at the surface. Such wells are more permanent and do not need such frequent maintenance or replacements.

The majority of smaller oases are concentrated around the villages and the wadi channels, the most oases, hand dug wells supply these oases with water. The wells near oases reach depths of 20 to 30m in the Quaternary accumulation, thus reaching the surface of the aquifers. Water occurs at 12m below land surface, and its temperature is between 38.9°C and 30.8°C. In hand dug wells in the wadi channels, water occurs some 8m below land surface.

The total number of water wells in Saudi Arabia is 28,863mcm, of which more than 50% are equipped with engines and pumps.

The cone of depression created by a pumping well is illustrated by water levels in control wells. The size of a cone of depression created by pumping depends on the size of the well and the proximity of the hydrological boundaries. Well pumping from ground of low transmissivity and storage will produce a steep cone of depression that does not extend an appreciable distance into the surrounding ground. A well will not yield water when its cone of depression reaches the level of the pump. Intake in big cities such as Riyadh, Makkah and Jeddah eventually demands a reduction in pumping rates in order to recover the water level. Better aquifers produce a shallow cone of depression of large diameter that cannot be lowered to the level of the pump intake by maximum pump discharge. The quantity of water discharge from a well is divided by the drawdown of water level in the well (Figures 4.5 and 4.6).

The requirements of an individual well is a major water production drill hole. In particular, geological and hydrological data are required to produce the detail of a suitable drill well, the most important of which are the thickness, character and sequence of strata to be drilled through and the degree of confinement of the aquifers,

Figure 4.5

Well in Um Al-Qura University in Mekkah used for Irrigation

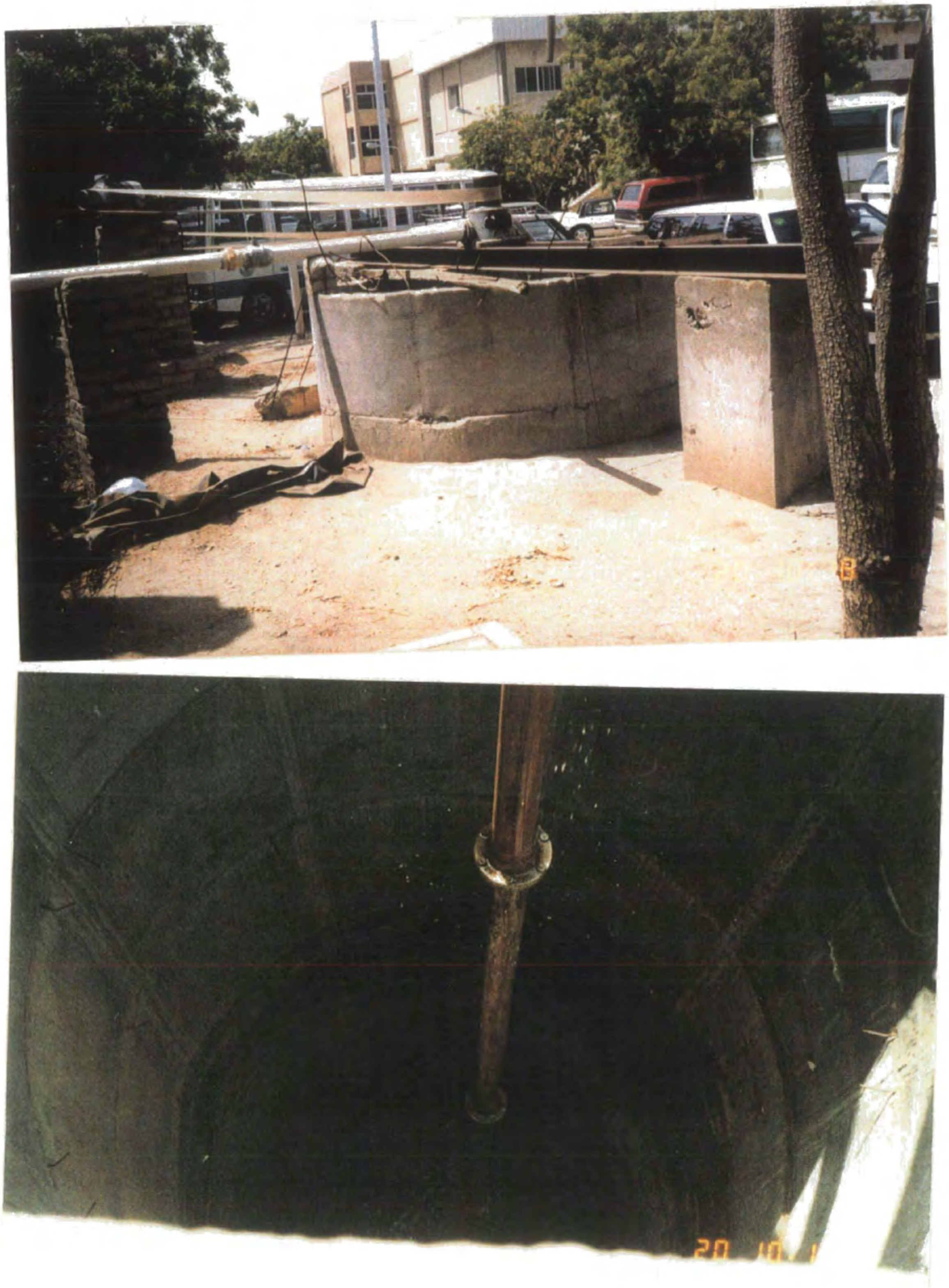


Figure 4.(6)

Water Well in Duba, Northern KSA

water level in the aquifers, and the quality of water, as well as the case histories of any wells previously constructed in the area. In most cases not all the information will be available (MAW, Department of Development of Water).

The form which can be pump tested using water. The water table must develop when the well is pumped since no flow could take place without a gradient toward the well.

4.7.4 Well development

As a basin is developed, and more wells are allowed to flow, both the gravitational potential energy of the aquifer and the potentiometric surface are lowered. Many wells were allowed to flow continuously, wasting water and gradually dissipating the aquifers' potential energy. Some wells have stopped flowing, and the yield of those still flowing have been reduced. The well in coarse sand and gravel could be pumped at a much higher rate, and the well in fine sand could be pumped a little harder, but the well in the sandy silt is already at its maximum production rate. It would not produce any more water, and over extraction of water supply use would result in a rapid draw- down of the water table, and due to this extraction the water table level. The recharge is sporadic and scattered, the overall regional potential is limited, because the rainfall is low, and flow of surface water are almost low. Although, many well yields are correspondingly low in the areas, a number of flowing wells still have yield at 32,000 m^3/s. Unless many more flowing wells are drilled, the surface, which is above ground level in most of the areas, probably is stabilised at its present level.

The yield from most wells can be improved by removing any fine-grained debris that may have entered the pores and fractures of the aquifer during drilling operations. Depletion is a gradual process indicated by two common and interrelated symptoms, decline of water levels and decrease in well yields. In many areas of the country, the water table of deep aquifers has steadily and rapidly been declining resulting in decreased water withdrawals and increased pumping costs. In some areas of the country, wells have been abandoned, while in other areas, wells had to be deepened and pumps had to be lowered to reach lower water levels. The low recharge rate of aquifers by infiltration, the introduction of engine-driven pumps, and uncontrolled water extraction over the last two decades resulted in a significant drop in the water table, particularly around Riyadha, Wadi Fatima, and Qutif. Consequently, the prior approval of the MAW is needed before drilling wells. Wells in limestone are often injected with acid to purge their fractures. This leaves the surrounding ground more porous and more permeable than it was originally. Pumping water from a well, surging water up and down a well, and playing jets of water against the walls of a well are methods used to develop wells.

Table 4.4 shows the number of wells extracting groundwater in six selected areas of the country. Interannual variation of groundwater is measured through a network of wells, as water pumped in mcm. Well hydrographs have been shown to correlate with climatology in summer and winter spells in various areas of KSA. The total number of wells is 28,853, and the total pumping rate is 1723.0 mcm/y.

Wells in the selected areas are located along the two strips of land either side of the wadi. Even within this relatively narrow aquifer there are considerable variations in properties between the areas. Loose sand in the aquifer in the well in area IV, allows faster pumping water than in wells in areas I and V. Pumping rates vary between 253.1-264.7 mcm/y.

Such shallow wells are also liable to pollution, especially when unlined or poorly protected at the surface. Output per well is modest and fluctuates, and there is considerable risk of contamination.

Figure 4.7 shows the well network in KSA. The location of wells is measured periodically or recorded continuously to show wells in principal or local aquifers and monitor the groundwater levels. The MAW maintains about 300 wells. Observation wells located around a pumping well provide information on the shape of the cone by indicating the drawdown at each location. Drawdown is the depth that pumping has lowered the water table in the aquifer. Substituting data on drawdown, pumping rate, and time since pumping began into a well- known mathematical equation can provide the aquifer's approximate permeability and storage coefficient in the region around the well. This information is crucial in the design of future production wells. Once the equation values are known, they can help predict future drawdown in the aquifer at any distance from the pumping well, also for planning to develop a water supply using an arrangement of several wells in a well field. The Figure 4.7 has distribution the well in the Arabian Shelf (sedimentary), and Arabian Shield, but almost the well in the sedimentary because it has a lot of the aquifers and easier to control water.

An estimate of the original hydraulic gradient can be made by using water level elevations of the walls. However, the eastern part of the country is affected by pumping more than the western part because the saturated thickness of the aquifers decreases to the east and south east. Field observation has indicated that the density of wells in southern wadis are considerably less than those wadis north and north east of it, yet the pumping depression surrounds it.

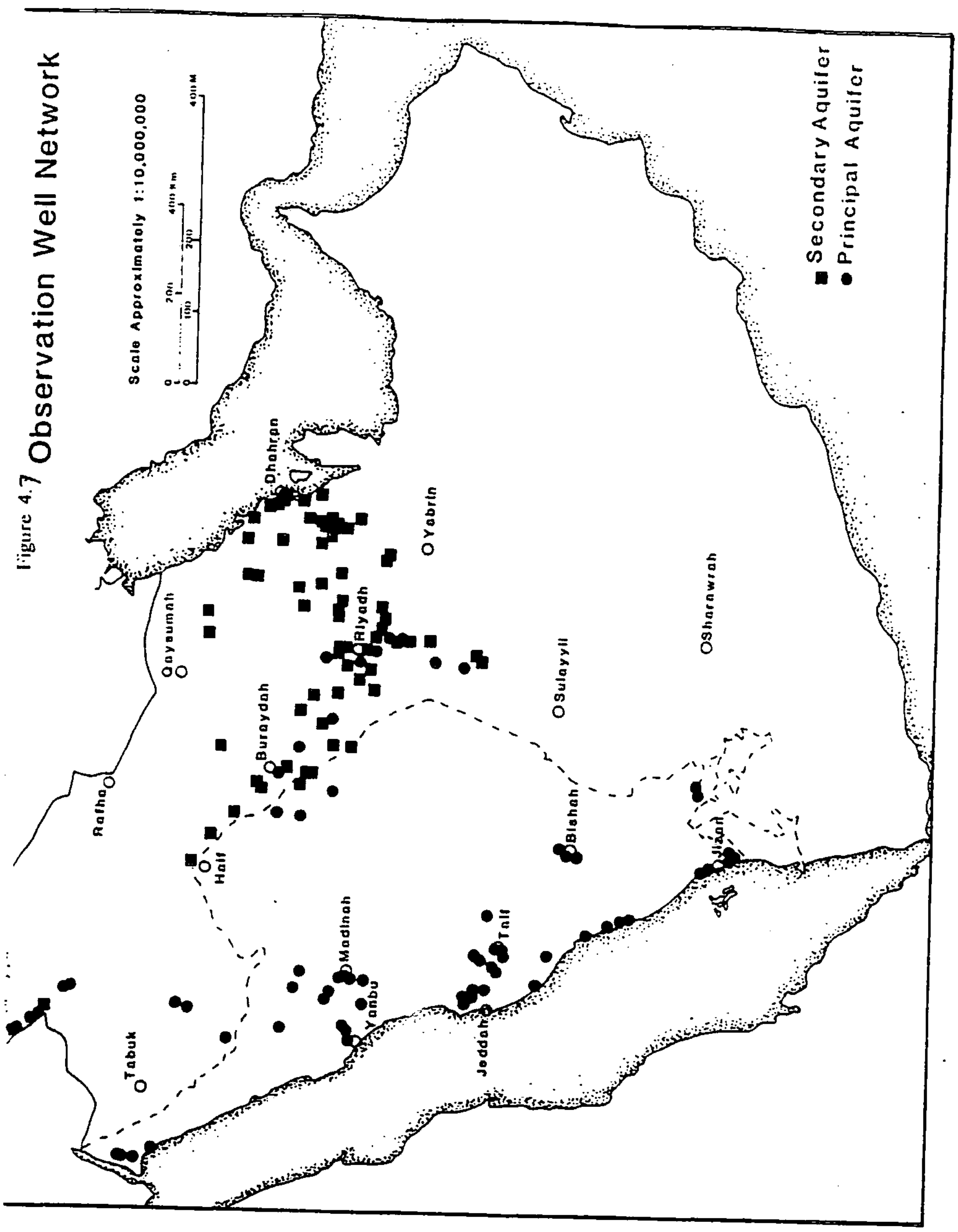


Figure 4.7 Observation Well Network

Table 4.4: *Number of wells extracting groundwater in selected areas of KSA*

Area	No. of Wells	Water pumped in MCM/year
Area I	3613	253.1
Area II & III	16938	442.2
Area IV	2058	628.4
Area V	4416	264.7
Area VI	+ 1838	134.6
Total	28863	1723.0

4.8 Recharge of Groundwater

Recharge is defined as all water inflow contributions to an aquifer. These contributions consist of rainfall, wadi bed or transmission losses and subsurface inflow.

Where an aquifer is unconfined by overlying rock, the water table is free to rise and fall as the volume of stored water changes. Such unconfined groundwater can be locally recharged by precipitation, seepage from streams, and dams. Groundwater may, however, be confined in an aquifer by overlying impermeable rock and may be at a pressure considerably above atmospheric pressure. Confined groundwater is naturally recharged only where the aquifer outcrops or contacts other aquifers.

Whilst water recharge depends primarily on climate, areas of natural recharge and discharge usually result from local geological conditions. In humid regions, more water infiltrates the soil and seeps down to groundwater than in arid regions, in which the opportunity for evaporation is higher (Al-Khatib, 1980; MAW).

The recharge comes from the direct infiltration of rainfall through sand dunes, fissured or bare rock surfaces, or along wadi beds. As the groundwater moves eastwards in a down-dip direction, it is often confined between aquicludes and so certain pressures are built-up. A proportion of the water eventually issues forth as submarine springs on the floor of the Gulf, while further amounts seep out in the eastern parts of the country to produce such famous oases as Al- Hassa.

It is not possible to put forward any generalisation about the ratio of recharge to storm run-off but the range is considerable and up to 50% of run-off can be taken into storage on an annual basis.

The apparently anomalous situation down the wadis is a reflection of many factors including the higher coefficient of run-off which characterises the steep incised wadis. Further, inland alluvial deposits in the wadis are thin and of small volume. True recharge conditions will not prevail until the coastal plain is reached and in this area the alluvial deposits of substantial thickness (1520m) are generally fully charged.

Deep percolation losses from irrigated fields are evidence that in some places recharge is easy to induce. In overfill where recharge amounts to a loss of useful water or an aggravation of waterlogging, the rate seems high. Generally, it is not feasible to inundate tens of thousands of hectares for the sole purpose of recharge. Evaporation loss would be high, and extensive flat areas generally are too valuable for other purposes.

Even at places where recharge is feasible, the inefficiency of aquifers as pipelines again is a drawback. So far as water availability is concerned, the effect is the same as physical transfer of water.

4.9 Groundwater and aquifers in Tihama Asir

4.9.1 Aquifers in Tihama Asir

In the north the Quaternary aquifer is, more or less, limited by the outcrops of the basement and the dike complex respectively. In principle, it forms a flat trough-shaped body with a longitudinal axis trending from northwest to southeast. The axis line at which the alluvials have developed a maximum thickness of at least several hundred metres seems to be located along the area flexure in the centre of the plain. East of the axis line the aquifer generally overlaps the Biyadh formation. To the west the aquifer overlaps the continental series of the Manisah-anticline. In the northeast between Jabal Hathah and Wadi Itwad, the aquifer lies directly on the Miocene dike rocks. In this space and east along the northwest trending Pleistocene fault, the aquifer diminishes rapidly due to the As Sir displacement. In the eastern area of Wadi Shahdan the base of the aquifer is the Jurassic Khums sandstone and the thickness of the aquifer is very small. This is caused by displaced to the southwest.

The 18 exploratory wells drilled revealed the existence of an aquifer which is very heterogeneous in its stratigraphic sequence. The sequence consists of various layers and lenses of sands, silts, clays, gravels and boulders. It seems that the areal extension of all layers which have been encountered is very limited. Therefore, it is not possible to correlate specific layers between wells.

Due to the high and strongly varying concentration rates of chloride in the groundwater, it is impossible to reveal any lithologic stratification in the subsoil of the Tihama Asir plain. This is caused by the fact that the resistivities of clays and sands are in the same low order since they are bearing salt water of high chloride concentrations.

(1) Two thirds of groundwater has H_3 (tritium) content greater than lTU (tritium unit), the maximum being 84 TU, suggesting that some of the groundwater was formed by rain after 1953.

(2) Water close to the Red Sea has no tritium content, implying long residence time, whereas in groundwater upstream of wadis the content is above 10 TU, thus implying a shorter residence time.

(3) Groundwater downstream of wadis and close to the Red Sea is recharged when surface discharge reaches these localities without experiencing any evaporation.

(4) Evaporation of groundwater becomes effective only in sabkhas where groundwater surfaces.

The water bearing sub-streams are mainly quaternary alluvial deposits. The groundwater in the alluvials are recharged by percolating of surface water through wadi beds originating higher up in the mountains. In the area, recharge is found to account for between 10% and 45% of runoff (Noury, 1984).

The hydrolgeological evaluation of the geoelectric survey has yielded the following results in detail:

a) The main groundwater body of the coastal plain is highly saline.

b) The complex of saline water is overlain by a body of fresh groundwater.

c) The fresh water reservoir actually is a subterranean channel- like system analogous to the present drainage pattern to former wadi systems. Wadi migrations have been caused by tectonic events and by basaltic volcanism which has altered the ancient land surface.

d) The maximum thickness of the fresh water body is more than 100m and has been located in the Wadi Baysh and Wadi Sabya areas.

Without regard to the groundwater flows connected with the present system, six subterranean fresh water flows have been located, from Wadi Baysh area in the north to the Wadi Harad area in the south.

In the Tihama Asir area, the only fresh water-bearing formations are the Quaternary alluvia, and where they exist, are the coarse layers on top of the Bayd formation.

The thickness of this alluvium varies from place to place, where ancient valleys, now filled up, were carried in the Bayd formation. The maximum known thickness of coarse formation is in the Wadi Khums borehole formation which is 230m of sand and clay.

Aquifers in Tihama Asir are short, narrow and thin, and there are multi-aquifer systems. In some locations, such as Wadi Jizan, one relatively isolated aquifer is found.

Only a few of the formations in the Tihama Asir area are potential aquifers: the Tertiary andesites and diabases contain brackish water; the greater part of the Bayd formation is either impermeable, or only barely permeable - it forms the impermeable sub-stratum of the area. In the Bayd formation, Miocene limestone layers are very rare and where they do exist they are very thin. The Quaternary basalt of Sabya and Abu Arish are too limited to serve practical interests as aquifers although they may be permeable.

There are several hundred local aquifers in the area, each completely independent from the others. They may be divided into two categories: the southern wadi aquifers and northern wadi aquifers.

The southern wadi aquifers have very variable underground discharges, even in the same wadi or from one wadi to another when the two wadis are adjacent. Generally, reserves are low due to their small storage capacity. The aquifers are generally less than 15 metres below ground level (see Chapter 2).

The northern wadi aquifers are fed by either *in situ* infiltration of wadi floodwater or by reinfiltration of wadi perennial water when it exists. Direct rainfall infiltration is usually low as the greater part of the rain is rapidly evaporated or used by vegetation. Near the sea sedimentary formations are intruded by sea water and the lighter freshwater overlies in Jizan area and in Tihama Ash Sham, totalling 78 mcm, whilst in other places fresh groundwater is limited (see Chapter 2). Quaternary alluvia deposits form the only important groundwater substrata.

Asir Mountain aquifers, while containing good quality groundwater, do not have sufficient storage capacity for extensive agricultural use (see Geology in Chapter 2).

The aquifers are generally unconfined but may be semi-confined or confined where silt and clay are interbedded with sand layers. The transmissivity generally varies from $1x10^3$ to $1x10^{-3}$ m^2/second and the coefficient of storage from $1x10^3$ to $1x10^5$ (MAW). The higher values were found in deposits near the centre of the wadis. Yields varied greatly from $2m^3$/second for dug wells with hand drawn buckets to as much as $10m^3$/second for modern well-designed cased-wells with pumps. The alluvial aquifers are generally long and narrow corresponding with the wadi channel, and they vary greatly in thickness (El-Khatib, 1980).

Wadis that drain westward from the crystalline rocks to the Red Sea coastal plain are short and steep. In the headwaters, the wadis have cut deeply dissected narrow valleys. Deposits of alluvium are rarely more than 100 metres wide and are generally less than 10 metres thick. Although aquifers in these wadis consist of coarse sand and gravel they supply little water because of their poor storage characteristics and restricted recharge. Large fans, which are formed at the confluence of the wadis and the Red Sea coastal plains, often grade into the alluvial aquifers of the plains. The alluvium in the wadis increases from 10 m thick in the upper reaches to as much as 100 m at the intersection with the plains. Along the Red Sea coast area, the deposits generally range from 10 to 20 m thick but locally can be much thicker. Aquifers in these deposits are mainly used for domestic and livestock supply, but locally some are used for irrigation. The aquifers have often been tapped by galleries and wells.

The movement of groundwater is not the same as would be found in sedimentary basins, because of the absence of continuous non-lithified strata. Since the water-bearing strata are more likely to be thicker towards the bottom of the wadi and towards orientation to that of surface run-off. However, the sub-surface flow is very often hampered by impermeable rocks and basement rock outcrops. Where the damming effect remains underground, it tends to hold the water in the water-bearing formation upstream and lower water table downstream. The variation in well depth, and in the water available, is a good illustration of the irregularity of the subsoil formation and water regime (in the Quaternary aquifer).

4.9.2 Groundwater in Tihama Asir

The depth of water below ground level varies between a few metres and 40 metres. The greatest depth at which water can be found is along a strip parallel to the plain, and situated at about one third of the distance from the mountains to the sea. This strip is broken in Wadi Baysh which already lies 40m below the ground level of other wadis.

The mean percentage of groundwater recharge is between 20% and 30% of the surface water. The availability of groundwater for irrigation in Tihama Asir area is calculated to be about 17 mcm, but only about 4.5 mcm are extracted (MAW).

The northeast area aquifer is limited both by the outcrops of the basement and the dike complex. The aquifer forms a flat trough-shaped body with a longitudinal axis trending from NW to SE. The axis line at which the alluvials have developed along a maximum flexure of at least several hundred metres seems to be located along the Jizan, overlapping the Baydh formation. To the west the aquifer overlaps the continental series of the Mansiyah anticline. In the northeast between Jabal Hathan and Wadi Atwad the aquifer lies directly on the Miocene dike rocks. In this area and east to along the northwest trending Pleistocene fault, the aquifer diminishes rapidly due to the As Sirr displacement. Therefore, beyond Wadi Atwad, groundwater occurrence is very limited.

In the eastern area of Wadi Shahdan the aquifer is the Jurassic Khums Sandstone and the thickness of the aquifer is very small. This is caused by the fact that in this area the most effective fault line of the eastern flexure zone is displaced to the southwest.

The MAW drilled some wells in the area, and revealed the existence of an aquifer which is highly heterogeneous in its stratigraphic sequence. The sequence consists of various layers and lenses of sands, silt, clays, gravels and boulders.

Layers and lenses of sand and gravel are interstratified everywhere in the aquifer. There is no evidence that the underlying beds of the Baydh Formation have been penetrated by any drilling. Due to the As Sirr displacement, this formation forms the bottom of almost dry alluvium in this area.

The characteristics of the groundwater flow and the quantitative methods for analysing the hydraulic properties of aquifers are dealt with in detail in numerous documents.

4.9.3 Well development in Tihama Asir

In spite of the complexity of the aquifer, formed of a thin sand and gravel channels in clayey series, there is a single alluvial water table, because of the connections existing between these channels.

The aquifer in the Tihama Asir is approximately 2 m^3/s divided as follows [Source: MAW]:

- 0.75 m^3/s in Wadi Khums and Khulab.
- 0.70 m^3/s in Wadi Dammad and Jizan.

- 0.45 m^3/s in Wadi Baysh and Sabya.

This underflow is not all available since pumping will lower the water table and consequently the fresh water / brackish water interface will rise. Therefore pumping should be restricted and confined to those areas where the interface rise would not cause contamination by salt water. The areas in which pumping is feasible are those where the fresh water bearing formations overlie the Tertiary impermeable series.

By respecting these precautions the extraction in the Tihama Asir could reach 1.5 m^3/s and the only effect would be the ingress of salt water in the lower plain which could not be cultivated anyway (MAW). It should be noted that this ingress of salt water inland would not lead to an increase of salinity in the water of the wells dug in the wadi beds near the sea. These wells supply water to some villages such as Al-Madayah and tap fresh water provided by local infiltration of wadi flood water.

Limited groundwater is found only in alluvial infilling, in and around wadi beds and in small amounts below the coastal plains of the Red Sea. The replenishment of this type of water depends upon annual rainfall. Delay in the rainy season or a short period of drought can easily cause these supplies to be depleted.

Interannual variation of groundwater recharge through a network of wells, when the number of observation wells have been observed. The hydrographs show a decrease of the piezometric surface an increase or a stabilisation of the water table. Well hydrographs have been shown to be correlated with climatology in terms of dry and wet spells over the region.

The government has carried out extensive investigation in wells in artesian conditions. In some areas the coarse sands in wadis are often covered by a roof of silt and clay and the aquifer is in a confined condition.

If leakage through the confining bed is negligible the drawdown distribution will be given by the nonequilibrium. provided that the aquifer can be considered in unconfined condition, homogeneous and isotropic, horizontal with an infinite lateral extension, the well fully penetrating the piezometric surface prior to pumping horizontal. Groundwater flow in sands of non-uniform thickness can be used to approximate the flow in aquifers of non-uniform exponential thickness.

A comprehensive programme of exploratory drilling was carried out in most of the basins and sub-basins of the area. All bore holes were geologically logged and, in many cases, the boreholes were logged for electrical resistivity, spontaneous potential and gamma radiation.

The total number of wells was recorded and water collected for detailed chemical analysis from approximately 3% of these. For 2.5% of the wells, field staff were assigned to record pump capacity details about the type of well. More than 18,500 wells in 391 communities were included in the inventory (MAW, Department of Water Development).

Water was collected from existing wells and boreholes during the well inventory in the field for electrical conductivity and temperature. In Wadi Jizan and Wadi Baysh sectors, 155 wells were surveyed. Their static levels range from about 30m to about 10 m, and then to about 3 m in depth from high to low elevations. These wells serve essentially for human and livestock needs, being used only secondarily to irrigate a few garden plots. In Saudi Arabia there are different length wells and depths from 70 m to 2500 m (see Chapter Two).

Conclusions

The key aspect of groundwater hydrology in an arid country such as Saudi Arabia is aquifer. In this chapter an analysis of the national pattern of catchments, a discussion on groundwater and a detailed examination of aquifers and wells.

Saudi Arabia

(1) The absence of a reliable and adequate surface water supply has resulted in a heavy reliance on groundwater. The groundwater is obtained from two types of aquifers: shallow aquifers and deep aquifers. The shallow aquifers contain a renewable water from rainfall and surface runoff water while flowing over wadis. The renewable groundwater is estimated at 950 $10^9 m^3/y$. The other type, deep and confined aquifers, contains a reservoir of water. It consists of nine principle aquifers and a series of local aquifers, collectively these aquifers contain 500,000 $10^9 m^3$ of proven water reserves. The principal aquifers hold approximately 335,000 $10^9 m^3$ and receive minor natural recharge at $1270.10^9 m^3/y$. The extensive use of the water stored in these deep aquifers makes this a non- renewable water supply.

(2) Many groundwater resources have been developed to meet increasing demands and to maintain Saudi Arabia's growth rate. Major groundwater resources, as a result, have suffered considerably from excessive withdrawals leading to rapid water level decline. In addition, some area groundwater users extract water in large quantities for agricultural purposes. Groundwater withdrawal control and use management are the most needed steps for better use and maximum benefits.

Four major aquifer characteristics may be adversely affected by exploitation of Saudi Arabia's groundwater: depth, water quality, and aquifer storage and production capacities. The latter are factors generally associated with shallow aquifers, while water quality and depth problems are usually related to deep aquifers.

The quality of groundwater resources in Saudi Arabia varies from area to area, however, most groundwater is classified as brackish and contains over 1000ppm of TDS.

(3) The present rate of groundwater withdrawal exceeds the rate of recharge and therefore there is a gradual decline in the static groundwater level. The quality of groundwater is deteriorating in the lower parts of the wadis, with wells poorly constructed and no strict control on groundwater utilisation.

There is no coordination between the farmers and the Water Development Department of MAW regarding the study of water resources. It should be strongly stressed that the work of the development of water resources of Tihama Asir should be carried out jointly with close cooperation and coordination between the farmers and DWD of MAW. This is in order to avoid repetition and duplication of the activities.

(4) In the period of development, groundwater was treated as though it was an independent resource. When the need for control arose, the lack of adequate major investigation was reflected in the disappointing results. Since agriculture is as important as other types of water use, the shallow aquifer cannot be, at present, an adequate source of supply.

(5) Since the major aquifers in Saudi Arabia receive little natural recharge, restricting water pumping according to a safe yield level would extend aquifer life, but at substantial economic and social cost. Such restriction would result in a major decline in agricultural production and farming income. Accordingly, owners have unlimited rights to use water as they wish which can result in excessive and wasteful pumping.

(6) The Ministry of Agriculture and Water requires application for drilling permits, but the lack of effective monitoring means that many wells are drilled without permission. Moreover, there is no law governing the use of water. The government can and should establish laws and regulations to administer and control water use.

Most of the country's water supply is groundwater, which must be regarded as a depletable resource, although it is estimated that fossil-water aquifers exist under as much as two thirds of Saudi Arabia's territory.

Tihama

(1) Water-bearing formations in the study area are:

  (a) alluvial deposits in the wadis and coastal plains of the Red Sea.

  (b) a few layerss of sand and gravel at the top of the Tertiary series.

  The most extensive water resources in the study area are due to:

  (a) the heavy rainfall from the Indian Ocean monsoons.

  (b) the great thickness of coarse and permeable layers interbedded with clay.

These resources are hardly used at the present time. Boreholes for irrigation have been drilled in Tihama Asir over the past few years, allowing several thousand hectares of land to be cultivated.

(2) The area has undergone rapid growth and tremendous economic development. Water demands also have increased greatly. Traditional water resources are not sufficient to satisfy the present high demands.

Until the end of the twentieth century, Tihama Asir's inhabitants depended for their water supply on shallow wells drilled in the area and wadis. The shallow wells drilled in Wadi Jizan Basin and Wadi Baysh are now the main shallow wells supplying the area.

Analysis of shallow groundwater development generally has its advantage among the area's water resources. Shallow water depth, good water quality and convenient location of wells minimise water development expenses.

(3) As a continuation and supplementary study, it would be valuable to use all the available information and interpretation of aerial photographs and satellite images. This first phase would take about a year.

A second phase could start after completion of the first phase. It would include hydrogeology, wells observation, piezometry, conductivity, transmissivity, infiltration, recharge and safe-yield and quality in order to come up with the detailed clear picture of the groundwater of Tihama Asir. This phase of the study would take about two years.

(4) Groundwater sources constitute only a proportion of total water requirements in Tihama Asir. The rate of groundwater withdrawal exceeds the rate of recharge. There is a gradual decline in the static groundwater levels.

The quality of groundwater is deteriorating in the lower wadi reaches. Wells are poorly constructed and there is no strict control on groundwater utilisation.

Groundwater and limited rainfall constitute the primary water supply for most inland areas at this time, and these sources will be developed as rapidly as possible to meet growing needs without jeopardising the resource base. Major water supply include drilling of new wells, repair and replacement of old wells, expanded and upgraded distribution networks, and construction of dams. The MAW has 760 wells dug or repaired to add to the 1,025 or more in the country with different purposes.

1. Groundwater is the most important water resource for Saudi Arabia and Tihama Asir. Nearly 80% of total cultivated area is irrigated with groundwater. About 50% of municipal water in large and small cities is obtained from groundwater while towns and villages depend entirely on wells.

   The sedimentary basin of the country contains the most important water-bearing formations and is composed mainly of sandstone, limestone, shales, marls and alluvium.

   In the eastern and southern parts of the country, sedimentary formations overlying the Basement Complex form the major outcrops, limestones and dolomites forming the major aquifers though, up until the present time, attention has been concentrated largely on the development of the sandstone aquifers because of the relatively high quality of their waters.

2. This is the Basement Complex of the west. Throughout much of the high western parts of the country (including Tihama Asir), igneous and metamorphic rocks outcrop to form a resistant and rigid Basement Complex of largely pre-Cambrian age. The permeability of such rocks is low and so groundwater tends to

concentrate in patches of alluvial deposits along the lines of the major wadis. The water can normally be tapped by shallow wells, but the quality and yield from such aquifers can vary considerably, dependent on local environmental conditions. There is a tendency for it to become more saline as the coastal plain and Red Sea are approached. The Basement Complex has the poorest prospects of rich groundwater, because it is essentially impermeable.

Chapter Five

Artificial Supplies

Introduction

Natural water resources in the KSA are largely limited to underground water which is used for both drinking and agriculture. Surface water is limited to areas around oases, and seasonal streams, particularly in the extreme south west of the country with its relatively heavy rainfall. Annual rainfall in the south western mountains is as much as 500 mm above other areas of the country (see Chapter 2), and this is the only region where surface water storage is possible. The wadis (see Chapter 3) which surround this belt of higher rainfall are characterised by periods of drought in summer, and floods in winter which carry the runoff from the bare mountains where there is minimal natural absorption of the heavy rains, that the considerable interest in the possibility of applying desalting technology to Saudi Arabia on a large scale has emerged as a counter measure to the unreliable and limited water sources. Throughout the country, rapid urbanisation has led to serious water problems as the meagre available resources have been called upon to supply an increasing population.

Present sources will become insufficient in the future. Most areas of Saudi Arabia experience year long water deficits. Population increases and progressive agricultural and industrial development have caused an urgent need for more water. The growing demand, however, cannot be met by traditional sources alone. Desalinated seawater has been used to make up the deficit. However, whilst seawater is seen as a potentially unlimited resource, it is not the sole response to the shortfall.

Water has always been subject to use, reuse and recycling. The natural water cycle, evaporation and precipitation, is one of recycling. Cities and industries draw water from surface streams and discharge wastes into the same streams, which, in turn, become the water supplies for downstream users. In the past, dilution and natural purification permitted re-use. The effects of industrial and demographic growth are such that waste water must be treated before it is discharged, in order to maintain the quality of the stream.

As a consequence of the inability of natural water sources in Saudi Arabia to meet the increasing demand for water, the government decided to make use of sea water by means of desalination. This process began in 1967, because Saudi Arabia currently has an abundance of fossil fuel and money, it is able to implement this costly technological solution to supply a major portion of its present and future water needs. Many coastal cities on the Red Sea are facing the problem of groundwater drying up. Therefore, a number of desalination plants have been established on the west coast. Many towns in the Eastern region are suffering from an increase in groundwater salinity as well as a decrease in the groundwater level, resulting in serious problems. Many desalination plants have also been installed on the east coast to produce potable water for the residents in this region.

Given the vital role desalinated water supplies are playing in water supplies in Saudi Arabia, a role which is seen as growing more and more as time progresses, it seems important that this study gives some detailed consideration to the nature of desalination and the processes involved. Further, the problems involved are investigated in order to assess the extent to which present plans relating to desalination are feasible in the long run. The growth of desalination capacity in Saudi Arabia has been the result of a combination of three main factors: the growth in demand for fresh water; the development of the multi-stage flash evaporator (MSF) which greatly increased the potential capacity of any desalination plant; and the accumulation of vast amounts of capital allowing the country to proceed with large scale desalination developments to a far greater degree than any other developing country, where lack of finance has severely limited their ability to install desalination capacity. From the earliest days of desalination in the country, the programme has been planned at two levels, short range and long range.

The short range programme has three aims. Firstly, to use recent technology to develop sources of desalinated water for water deficient areas where natural and economic conditions permit. This is seen as being particularly urgent in those areas of western Saudi Arabia in particular, where a combination of limited groundwater resources and rapidly growing water demand are causing serious water deficits to develop. Secondly, desalination is to be used as a replacement for groundwater supplies in those areas where such water is generally poor in quality and is deteriorating as a result of over-extraction. Thirdly, the short range programme seeks to meet emergency water requirements in certain areas (SWCC).

The long range desalination programme of the country aims at developing a desalination capacity capable of accommodating the water requirements of long term economic and demographic development plants. Thus, the programme has four main facets. Firstly, to generally develop the sea as a major source of potable water. Secondly, to develop and implement programmes to advance the technology of water desalination (SWCC). These schemes aim basically to reduce the cost and increase the efficiency of desalination processes and the subsequent storage and distribution networks. Thirdly, the programmes aim to develop and implement programmes with the aim of making desalinated water replace, whenever possible, natural sources as the main supply for the cities and towns as well as industry in order that natural resources can be released for agriculture (SWCC). The fourth long term objective of the programme aims at developing desalination technology to a point where it can in fact be used for agricultural requirements itself. Nevertheless, as will be seen, despite extensive research into developing more economical desalination techniques, success has been limited and desalinated water remains far too expensive to be used to irrigate the vast majority of the crops grown in the country.

It can be seen therefore that the majority of Saudi Arabia is opting for a high technology solution to their long term urban water shortage problem. Vast amounts of capital are being spent and at the moment desalination plants are providing a large percentage of urban water requirements (SWCC). However, it is suggested that this programme is being undertaken in a somewhat foolhardy manner with little account being made of the long term implications of a large scale desalination programme in terms of the very high capital costs and running costs involved. Furthermore, it is argued that this is a serious problem since at the moment concentration on desalination projects is eclipsing the real priority of attempting to introduce a more rational use of water in both urban and rural areas as part of a long term water development strategy which will lay the basis of continuing water supply into the post-oil era.

The reuse of treated effluent is most applicable where large volumes of water are used and the wastes are not too contaminated. Industrial wastes, on the other hand, may be heavily contaminated and therefore may offer little potential for the recovery of clean water. The location of the treatment plant and the possible transportation of the renovated water are important considerations. A waste water renovation plant need not always be located at the same place as the municipal waste water disposal plant.

Waste water is classified according to the source: domestic, industrial, and agricultural. Effluents from industrial plants are not uniform in their composition and may contain toxic compounds, as mentioned above. Such effluents may have to be disposed of. Domestic effluents can be estimated. Accordingly, the resultant waste water composition is always made up by contributions of both supply water concentrations and mineral pick up during use. The amount of water required to produce the same yield of an agricultural crop increases fivefold if the concentration of the total dissolved solids in the irrigation water increases from 1 to 4 m^3.

This chapter examines a number of responses to the water deficit. Technologically, the focus has been on desalination plants and processes. Other responses include reuse, treatment and better water management. In the KSA, each of these responses is being taken up in some way. In Tihama Asir, however, perhaps because of the greater abundance of good quality groundwater, there are no artificial water supplies. Tihama Asir is one part of Saudi Arabia where natural water is the only source of water used for agriculture and drinking, and is sufficient to meet domestic water demand.

5.0 Salinity of water

The word salinity is used both in a general sense and as a technical term to describe the saltiness of water. As a technical term salinity was used originally in relation to sea water and was defined as the total of dissolved solids, expressed as grammes of salt(s) per kilogramme of solution. When referring to fairly concentrated solutions, as in the ocean (sea), the salinity was often expressed as parts per thousand or as a percentage by weight of salt to water. Thus, sea salinity of 35 parts per thousand or 3.5%.

Water can be classified several ways based on chemical quality. Probably the simplest is that proposed by the U.S. Geological Survey [SWCC]:

Total Dissolved Solids (TDS) parts per million (ppm)	
less than 1,000:	fresh
1,000-3,000:	slightly saline
3,000-10,000:	moderately saline
10,000-35,000:	very saline
more than 35,000:	brine

Some people use the term brackish for water from about 1,000- 10,000 ppm TDS. Terms such as fresh, brackish, saline and salty, when applied to water quality, are not universal. The terms depend on individual tastes and on the use for which the water is intended.

There are various methods by which saline water may be converted into fresh potable water of low salt content, and various factors which determine the selection of the most appropriate method of desalination. These include:

a. The composition of the sea water. On the average, sea water contains 35,000 parts per million of total dissolved solids (TDS). However, the TDS of the water in the Arabian Gulf averages 56,000 at Al-Khobar and varies from 38,000 to 43,000 in the Red Sea at Jeddah.

b. The temperature of the sea water feed, and other natural factors. In the design of desalination plants, temperature must be considered in order to ensure that the plant will yield its design capacity at the chosen design temperature. If the temperature of the feed increases or decreases, productivity is affected.

c. Production costs of water and electricity. The process must be selected to yield the optimum capital costs and operating costs, based on the latest advances in desalination technology.

Initially, the operation and maintenance of these plants along with the selection and hiring of the necessary trained personnel, are entrusted, under contract. After that the corporation itself assumes the responsibility for all functions including spare parts and personnel. Later, SWCC was able to extend this principle to the operations and maintenance of all its plants. This become possible because from its earliest days the Corporation had paid special attention to the training of Saudis to enable them to perform these tasks efficiently.

5.1 Desalination

5.1.1 Introduction

Area investigations and other surveys carried out so far showed that in parts of Saudi Arabia, regardless of the quality and quantity, can be easily encountered. However, there are certain areas like most of the northern sector of the Red Sea coast, the Arabian Shield, and north eastern Saudi Arabia, where the groundwater is not satisfactory for human consumption. As the government policy was not to leave this problem unattended, the conversion of sea water or desalination or brackish water has been adopted.

The idea of desalination as a supplementary source of potable water, in order to save underground water for agricultural use, was conceived as a means of supporting the immense and rapid physical development, the cultural and economic progress and the population increase forecast for the KSA. It is proving to be a useful response to the problem of providing sufficient potable water.

It is encouraging that research into the production of fresh water from the sea continues to be successful. As a result of investigations into various processes of desalination, the flash distillation process was selected for use in smaller, single purpose plants to produce distilled water and power from a single fuel source. The distillation plants located on the western shores of Saudi Arabia along the Red Sea Coast use heavy fuel oil from Jeddah refinery, and plants on the eastern shore along the Arabian Gulf use natural gas as this fuel is abundant on that side of the country (SWCC, 1983).

Sea water was first used as a resource to produce fresh water in Saudi Arabia in 1907 when a desalination *Kindassa* (condenser) was installed in Jeddah. In 1928 the original condenser, fuelled by coal and wood, was replaced by two newer models. These condensers produced between 4,800 and 6,400 m^3/day of fresh water.

As a result of these desalination objectives, desalination plants spread throughout Saudi Arabia subsequent to 1988 as shown in Table 5.1 and Figure 5.1 which give the capacities of the various desalination plants. Table 5.1 shows that desalination plants in Saudi Arabia have been operating on the Red Sea and Arabian Gulf coasts since 1969. More desalination plants have been built to meet the increasing municipal demand for water (Figure 5.1). The first were built in Duba and Al-Wajh with a capacity of 140,000 million gallons/day (mg/d) (230m^3/d). During 1973 and 1974 plants were built at Khafji and Al-Khobar in eastern Saudi Arabia with a production capacity of 7,620,000 mg/d (213.5m^3/d) during the first phase. Between 1976 and 1979, the first and second phases were built in Umluj-Jeddah, Duba, Al-Wajh and Farasan Island in western Saudi Arabia with a capacity of about 33,668,000 mg/d (120.8m^3/d). In the eastern part of the country, at Khafji Al-Saree, production capacity is 330,000 mg/d (200m^3/d). From 1980 to 1988, on both coasts, desalination plants were built in Haql, Medina and Yanbu, Rabigh, Jeddah, Jubail, Khobar, Al-Birk, Jubail and Makkah and Taif. These produce about 373,850,000 mg/d (1900.9m^3/d) of water, with an electric power production capacity of 3,529 MW/day. Saudi Arabia now produces desalinated water at the rate of 384,978,000 mg/d (about 508,000 m^3/day). The largest plants in operation are, in order of production capacity, Al-Khobar, Jeddah and Jubail respectively, producing in total about 170 mg/d (about 456.12 mcm/d).

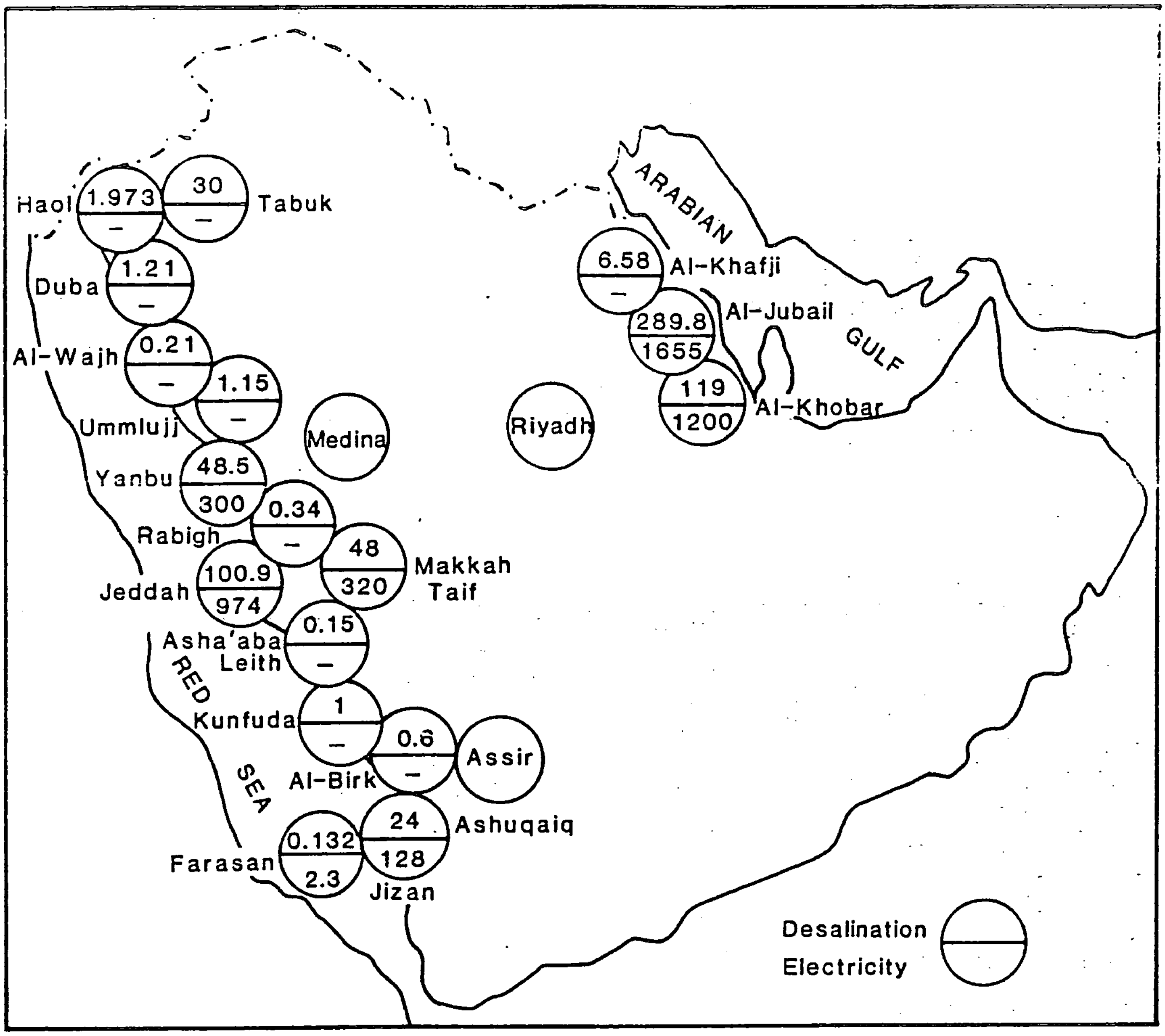
Table 5.1: Desalination Plants in Saudi Arabia

Plant	Site	Start up date	Capacity million USG	Power M.W.
Duba (Phase 1)	North-West on the Red Sea	1969	70,000	-
Al-Wajh (Phase 1)	North-West on the Red Sea	1969	70,000	-
Umluj (Phase 1)	North-West on the Red Sea	1976	120,000	-
Three quick desalination units in Jeddah	West of the Red Sea	1976	198,000	
Jeddah (Phase 2)	West of the Red Sea	1977	10,000,000	84
7 desalination units, Reverse Osmosis Method, Jeddah	West of the Red Sea	1978	3,300,000	-
Jeddah (Phase 3)	West of the Red Sea	1979	20,000,000	200
Duba (Phase 2)	North-West on the Red Sea	1979	120,000	-
Al-Wajh (Phase 2)	North-West on the Red Sea	1979	120,000	-
Unluj (Phase 2)	North-West on the Red Sea	1987	1	-
Makkah and Taif (Phase 1)	West on the Red Sea	1988	40 Makkah 25 Taif 15	325
Farasan Island	South-West on the Red Sea	1979	120,000	75
Haql (Phase 1)	North-West on the Red Sea	1980	120,000	-
Medina and Yanbu (Phase 1)	West on the Red Sea at Yanbu	1980	25,000,000	250
Jeddah (Phase 4)	West on the Red Sea	1981	50,000,000	500
Rabigh (Phase 1)	West on the Red Sea	1981	240,000	-
Al-Birk (Phase 1)	West on the Red Sea	1983	500,000	-
Khafji (Phase 1)	North-East on the Arabian Gulf	1974	120,000	-
Al-Khobar (Phase 1)	East on the Arabian Gulf	1973	7,500,000	-
Khafji Al-Saree	North-East on the Arabian Gulf	1979	330,000	-
Jubail (Phase 1)	At Ein Subab on the Eastern Coast on the Arabian Gulf	1981	20,000,000	300
Khobar (Phase 2)	East on the Arabian Gulf	1982	50,000,000	500
Jubail (Phase 2)	Eastern Coast on Arabian Gulf	1983	210,000,000	1295

Figure 5.1

Projects Proposals by Saline Water Conservation Corporation

1988 Date?



Although it was as early as 1928 that His Majesty the late King Abdul Aziz ordered the installation of conventional boiler/condenser/units for distilling sea water into potable water, Kuwait began its desalination programme much earlier than Saudi Arabia. The KSA commissioned its first plant in 1966, which was opened at Jeddah in 1970. The development and maintenance of desalination capacity in Saudi Arabia is the responsibility of the Saline Water Conversion Corporation (SWCC) which was established in 1974 in recognition of the importance of desalination as the means by which to meet the growing needs of the population and the expansion of industry and agriculture. KSA is amongst the most developed countries of the world in terms of desalination capacity.

As well as desalinated water, waste water is also being considered as a new water source in KSA, although the flow rate of such appears to be rather small compared with the various water demands now in evidence. The move towards the use of waste water highlights the growing needs of the population and expansion of industry and agriculture. The most likely uses for such non-domestic demand are ornamental irrigation and in industry.

Conservation measures would save much water that is now wanted. Manufacturing processes can now be altered to cause less pollution, and water in industrial plant can be recycled. Nevertheless, cities and industries still require large amounts of fresh water.

In recent years, considerable interest in the possibility of bringing desalination technology to Tihama Asir. As in other areas of Saudi Arabia, water sources in Tihama Asir are unreliable and limited. The argument for desalination is strong because the natural water supply is getting short, and competition between human and industrial demands and those of agriculture is placing an increasing strain on limited resources. The government has plans to extend desalination to the Tihama Asir area after Abha, and/or when the population increases as a result of agricultural and industrial development. The government intends to spread desalination to other Saudi Arabian areas by 1997.

Since the first plant was started, many desalination plants have been established on the west and east coasts. Some have the single purpose of water production, others have the dual purpose of producing both potable water and electricity (see Table 5.1). The desalinated water produced presently is mainly for domestic and industrial purposes. Groundwater will gradually be used exclusively for agriculture. Not only do the coastal cities utilise the desalinated water, but also some of the internal cities such as Riyadh and Makkah which need a greater water supply. The total volume of desalinated water is growing as a result of the increase in the number of desalination plants. Between 1970 and 1980, desalinated water supplies increased more than eight times, rising from about 16,400 to about 143,000m^3/d. At the present time, Saudi Arabia is considered to be the largest producer of desalinated water in the world (Ministry of Planning, Saudi Arabia, 1982).

There are now many desalination plants in Saudi Arabia along the Red Sea coast (63 plants) and the Arabian Gulf (10 plants). In order to illustrate some of the details of desalination plants, a number of typical plants have been selected as examples:

- Jeddah - Red Sea
- Al-Khobar - Arabian Gulf
- Omlaj - Red Sea

Jeddah

As a result of rising standards of living in the city, the expansion of industry, an increase in the population, the increased demand for water for domestic, industrial and agricultural purposes, together with the drawdown of the groundwater level, all seriously affecting the agricultural areas through increasing salinity, a desalination plant was constructed.

This desalination plant consists of:

a. Power and desalination installation with two oil-fired boilers, two turbo-generators, two desalination units of the long tub multi-stage flash type, with a combined output of sea water.

b. Transmission pipeline connecting the water refinery south of the city to the desalination plant north of the city with all its associated equipment.

The government decided (Phase 2) to expand the capacity of the desalination plant to 37,850 m^3/day with 100 MW of electricy production. Phase 3 expansion is to 75,000 m^3/day with 200 MW of electricy production. Phase 4 expansion is to 189,000 m^3/day with 200 MW electricy production.

Heavy oil is used as fuel for the desalination plant in Jeddah. Phase 2 consists of two units each consisting of a steam turbo-generator and multi-stage flash evaporator, Phase 3 consists of four units each consisting of a steam turbo-generator and multi-stage flash evaporator.

The first large scale desalination plant began operation in Jeddah in June 1970 with production capacity of 6.9 mcm/year of potable water. In 1983 expansion of the sea water conversion plants had grown to the point where Jeddah had a total production capacity of about 142 mcm/year, and another plant with a capacity of 41.5 mcm/year was constructed in Jeddah.

The production output of the Jeddah plant was decided having determined that the existing supplies from desalination plants and wells which then totalled 208 mcm/year, would furnish an adequate supply of water only until 1995 by which time the estimated water demand would be 207 mcm/year. Further, the water demand forecast indicated that by the year 2000 an estimated 329 mcm/year would be needed.

A reverse osmosis plant was desalinating water for Jeddah by 1983, and another such plant was under construction in Birk. Technological advances enabled this process to become economically competitive with multistage flash process (by the early 1980s). The reverse osmosis process uses less fuel, and is potentially more cost efficient than the multistage flash process.

The plant came on stream in October 1970 with a daily capacity of 5 million gallons, and generated 50 MW of electricity. In 1980 it was producing 58.1 million gallons and generating 600 MW of electricity.

Al-Khobar

Water supply for the area is tapped from about 90 wells in the Alat and Khobar formations. Water is the vicinity suffers from high salinity, causing serious problems, including corrosion of pipes, which renders the water unfit for domestic use. Water salinity is still increasing and there is a considerable depression of the groundwater level.

In view of the expected increase of population in the area, MAW undertook to install a desalination plant, with a capacity of 28,390 m^3/day. The designs of the structures are listed below:

a. A multi-flash sea water desalination plant, with a capacity of 28,390 m^3/day with all basic equipment;

b. an efficient and reliable gas-turbine power station, complete in all details, to generate a minimum continuous net output of 5000 KV and sufficient standby capacity;

c. five blending stations in the five towns of the east, where desalinated and brackish water from local wells will be mixed and pumped to elevated tanks for distribution. The quality of the mixed water would be in the order of 1000 ppm total dissolved salts (TDS).

Phase 2 would increase production to 89,250 m^3/day and 500 MW of electrical power. In Phase 3, the figures would be 151,400 m^3/day and 400 MW. Phase 2 consists of 3 units each consisting of a boiler and multi-stage evaporator, and phase 3 consists of five units each consisting of a boiler, steam turbo-generator and multi-stage evaporator. The two phases will supply domestic water to most of the eastern towns and villages.

In the Al-Khobar area a seawater desalination plant has been constructed at Aziziyah on the Arabian Gulf to supply the towns of the Eastern Province with potable water. The plant is now being commissioned for preliminary operation and will be put in continuous operation at a later date with a daily production of sea water and generating electricity.

It was estimated in 1983 that the water demand for Al-Khobar was 58 mcm/day, by 1990 would be about 119 mcm/day, and would continue to grow due to the growth of industrial centres, the increase of the population and a greater demand for agricultural production. It was further determined that additional increases in the water supply for Al-Khobar would have to be supplied from desalinated supplies because of declining water levels in the artesian system. By the year 2000 it is estimated that 190 mcm/day will be needed. Commissioning of the desalination plant at Al-Khobar has been agreed. It has a 40 km pipeline to carry water from the desalination plant to Dammam, Seihat, Safwa and Qatif.

Omlaj

Omlaj desalination plant on the Red Sea had an inital production capacity of 454 m^3/day. In response to an increase in demand for domestic water use, Phase 2 increased production to 3,785 m^3/day with 10 MW of electrical power. It consists of a boiler and multi-stage evaporator.

The Omlaj desalination plant went on stream late in 1975 with a daily production capacity of sea water. In 1983 daily production of sea water increased. It was estimated in 1990 that the water demand for Omlaj would be 1.4 mcm/day, and about 1.8 mcm/day by the year 2000 due to the growth of the population and the development of industrial and agricultural production. Water supplies are expected to continue to be provided from groundwater sources and desalination.

The rated capacity of desalination plants in the KSA has risen from 18,935 m^3/day in 1970, to 413,160 m^3/d in 1984, an increase of 81 times, corresponding to an average annual increase of 36.3%.

The water supplied by the desalination plants is estimated to have risen correspondingly from 46,000 m^3/d to 330,600 m^3/d, an average annual increase of 30.2%.

The largest single plant is located at Jubail with a capacity of 240 m^3/d. The plants at Jeddah and Al-Khobar have a rated capacity of 88.5 m^3/d and 57.5 m^3/d respectively. The plant supplying Madinah and Yanbu has a capacity of 25 m^3/d. The remaining capacity of 2.2 m^3/d consists of eight small plants at Al-Khafji, Duba, Al-Wajh, Omlaj, Farasan, Haql, Rabigh and Al-Bark.

The decision has been taken that the cities and towns on both the Red Sea and Arabian Gulf coasts will be supplied with water from desalination plants. Although the plants are heavy users of energy, Saudi Arabia can well afford this.

The purpose of this chapter is to describe desalination and recycling treatment processes and give examples of combinations of processes to achieve a variety of water qualities for reuse.

5.2 Production Costs of Water and Electricity

Investigators have attempted to determine realistic estimates of the costs involved in producing much of the raw water in Saudi Arabia, but these efforts have been less than entirely successful.

The whole programme was intended to add more than 503,568 m^3/day between 1976 and 1988, around ten times the present capacity, and some 345,475 MW of electricity generating capacity, or twenty times the present. Projects already formulated for completion after 1988 amount to a total 50% larger than even this ambitious programme. The total planned investment is over $7 billion (26.25 billion SR).

The total construction costs of plants for the production of domestic water in the country are as follows:

a. Jeddah Desalination Plant (three phases): SR 229 million (about £38,166m, $76,333m) from 1979-1981.

b. Al-Wajh and Duba Desalination Plants: SR 14 million (about £2,500m, $4,666m) from 1969-1979.

c. Al-Khobar Desalination Plant: SR 289 million (about £49.23m, $77.1m) from 1973-1982.

d. Omlaj Desalination Plant: SR 10.8 million (about £1.84m, $2.88m) from 1969-1987.

e. Al-Khafji Desalination Plant SR 12 million (about £2.044m, $3.2m) from 1974-1979.

f. Makkah and Taif Desalination Plants SR 5 billion (about £852m, $1333 billion) in 1988.

g. Abha Desalination Plant: SR 1.6 billion (about £200m, $424.950m) in 1989.

Of all the non-conventional methods for supplying water, desalination is now wide-spread in Saudi Arabia. It is, however, a very expensive source of water supply, estimated to cost about 3.75 SR (about $1.003) per m^3 based on an energy cost of 300 SR ($80) per ton between 1976 to 1988.

The cost of establishing such massive desalination projects is, of course, huge. In the current five year plan (1985-1990) alone, 300 million SR ($80 million) are for the construction of desalination plants. Although construction of desalination plants is proceeding rapidly at the moment, a number of problems are likely to arise which in the long term, may affect the continued viability of the plants.

The most basic component of the cost structure is the cost of supplying raw water, with or without transportation through one of the usual engineering conveyance systems, such as pipelines. Production costs are in the range of SR 20,936.2 billion (about £3 billion). Since most water systems in Saudi Arabia have a fairly limited geographical range, the transportation costs tend to be only moderate.

The true cost to the economy should also take into account the cost of generating electric power, a major production input, and of transmitting it. However, many modern desalination plants also include their own electricity generation, and so there may be the additional output benefit of surplus electricity available for other uses.

The costs of fresh water from a desalination plant should be generally considered is four categories:

a. Capital including original cost of equipment

b. Amortisation

c. Labour

d. Fuel source or energy

The attempted to determine realistic the costs involved, but those efforts were less than successful, in part because power is supplied with charge or subsidised rates. The studies of various kinds such as optimum size, type and location of single or dual purpose plants, administration and operation of the desalination and power plants and associated facilities, control of all process variables in the production of water, and carrying out the necessary operational and preventive maintenance of all equipment.

Since SWCC plants continue to increase in size and complexity, they require highly qualified trained labour for their operation and maintenance. It has trained employees in the facilities staffed, and also designated the necessary basic qualifications for further study and training in various foreign countries.

Each process must first satisfy the criterion of "will it work?" and then, if further development is to be justified, it must show a cost advantage in one or more of the above categories.

The cost estimates derived in this fashion have been criticised, however, because they do not include the cost of water distribution, but so long as one is fully aware of this limitation, the value of economic analysis that results can still be meaningful in offering guidelines for project evaluation.

The desalination of water at a price so low that no profit is earned does not allocate scarce water resources efficiently. It does not allocate the water to those who can make the most efficient use of it, as measured by their willingness to pay. At a lower price, there will be an excess of demand for water and some non-scarcity price-rationing rule will have to be used. Therefore there is incentive on the part of that product to monitor his income, or his expenditures, and hence his treatment costs. The investigators found that such costs were estimated to be in the range of SR 10 /m^3 to SR 45 /m^3 (about £1.50/m^3 to £6/m^3, \$2.66/m^3 to \$12/m^3) for desalination.

5.3 Methods of Desalination

Distillation Processes

Distillation processes can involve the production of fresh water and the generation of electricity:

a. Conventional distillation

In simple distillation, vapour produced by heating sea water at ordinary pressure is condensed, cooled and collected. The use of solar energy for heating the sea water is being studied to determine how to reduce production costs. The use of solar energy is still in the experimental stage.

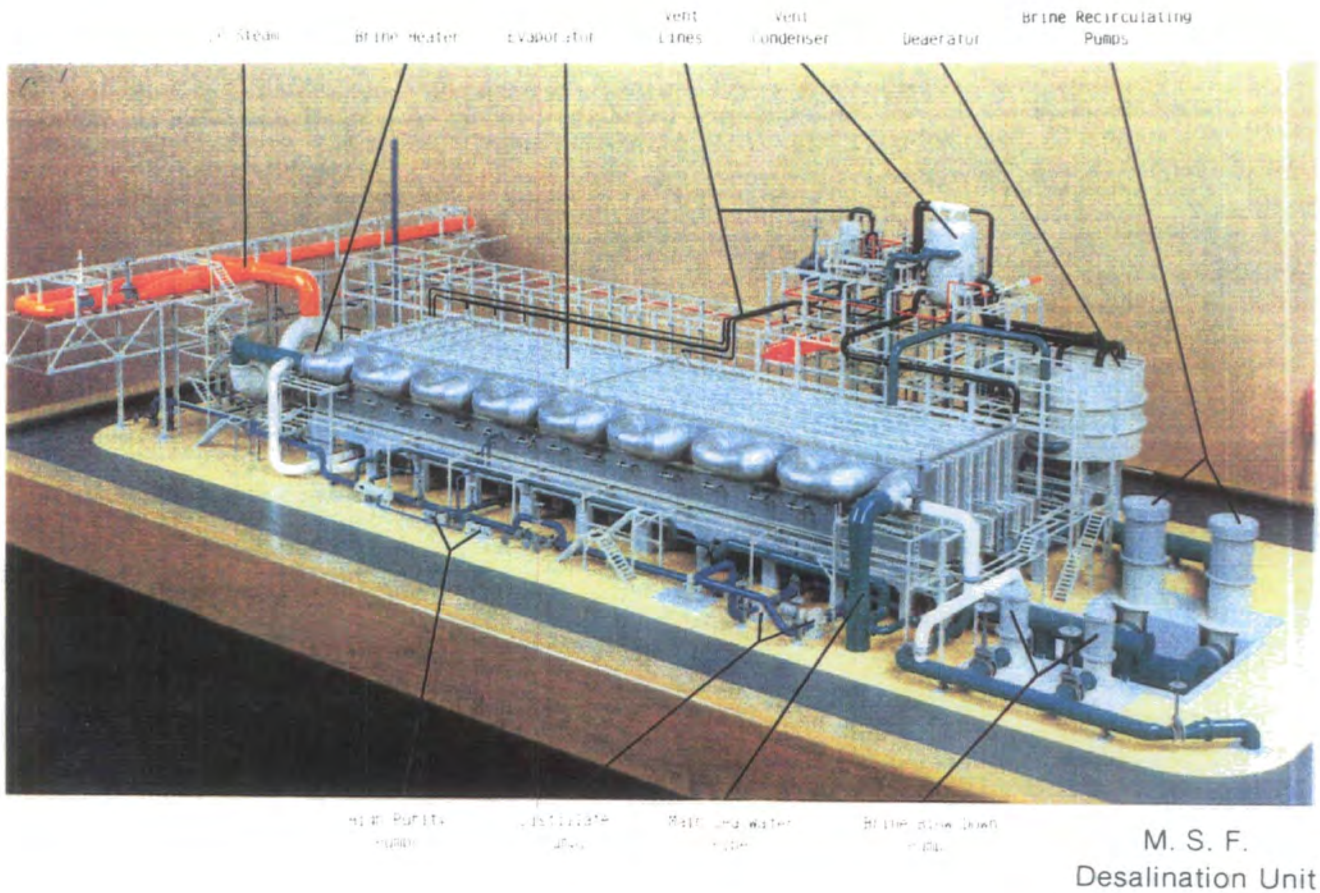
b. Multistage Flash (MSF) Distillation

This method depends on the fact that the boiling point temperature of a liquid is proportional to the pressure: as pressure decreases so does the boiling point temperature. In the MSF process, the heated sea water is conducted into successive chambers at successively lower pressures. Under these conditions, additional boiling takes place in each of the chambers. The vapour produced condenses on cool surfaces and is collected as distilled water. Most of the largest desalination plants use the MSF process (Figure 5.2).

Sea water boils at a temperature lower than 100°C when under reduced pressure. When a liquid condenses, it gives out heat (latent heat of condensation). This heat

Figure 5.2

A Simplified Description of Desalination Unit



can be used to heat sea water which is at reduced pressure. If the pressure above the heated sea water is reduced to below that at which it would boil at the temperature reached, then a quantity of vapour is released into the space above without turbulent boiling. This stage of flash evaporation supposes that the condensation takes place on tubes which are continuous from one stage to the next and through which cold sea water is passing in the opposite direction. In the first evaporator, water vapour condenses on the outside of the tubes. There are many tubes carrying cold sea water in order to maximise the surface area for condensation, and therefore increase the overall rate of production of condensed water. The condensate (distilled water) is collected. In the second evaporator, the incoming sea water in the tubes is cooler than in the first evaporator, because it is coming in the opposite direction supplied from the sea, and more water vapour condenses on the tubes, thus warming up the incoming sea water.

5.3.1 Description of a Multi-Stage Flash (MSF) plant:

An MSF plant, producing fresh water and generating electricity, consists of two parts: the desalination plant and the electricity power plant. Figures 5.2, 5.3, 5.4 show MSF plants, an engineer's flow and a multiflash, long tube desalination plant at Jeddah and Al-Khobar with electricity from the power station being used to pump the desalinated water by pipeline to Taif

Figure 5.3 shows a general view of the desalination plants in Jeddah, west coast. The Figure 5.4 gives a view of the desalination pump station to pump seawater to Al-Taif from Al-Shaba plant.

In also producing electricity, the multistage flash distillation plant has an economic advantage over plants using other methods of deriving potable water from saline

Figure 5.3

Desalination Plant at Jeddah

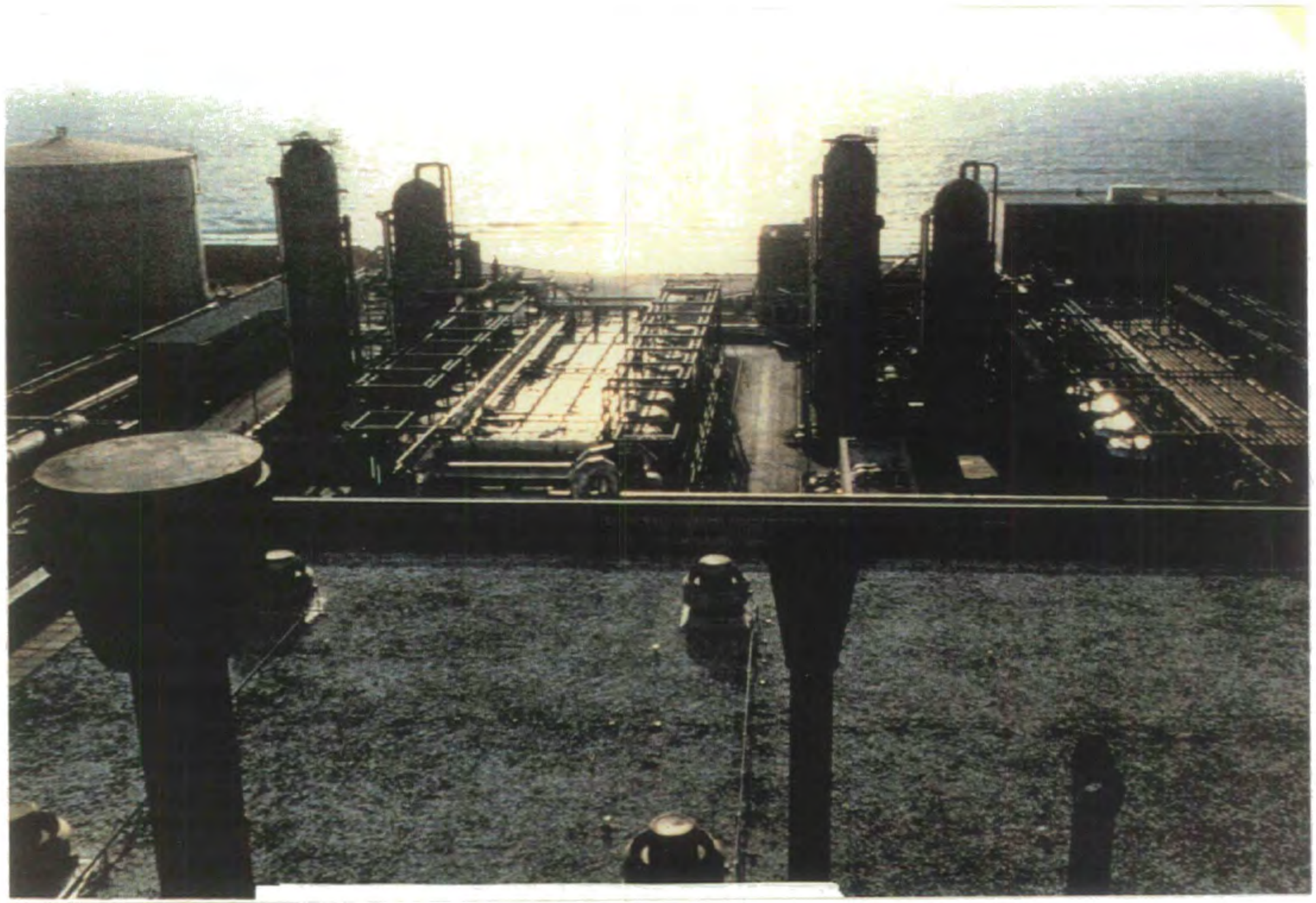
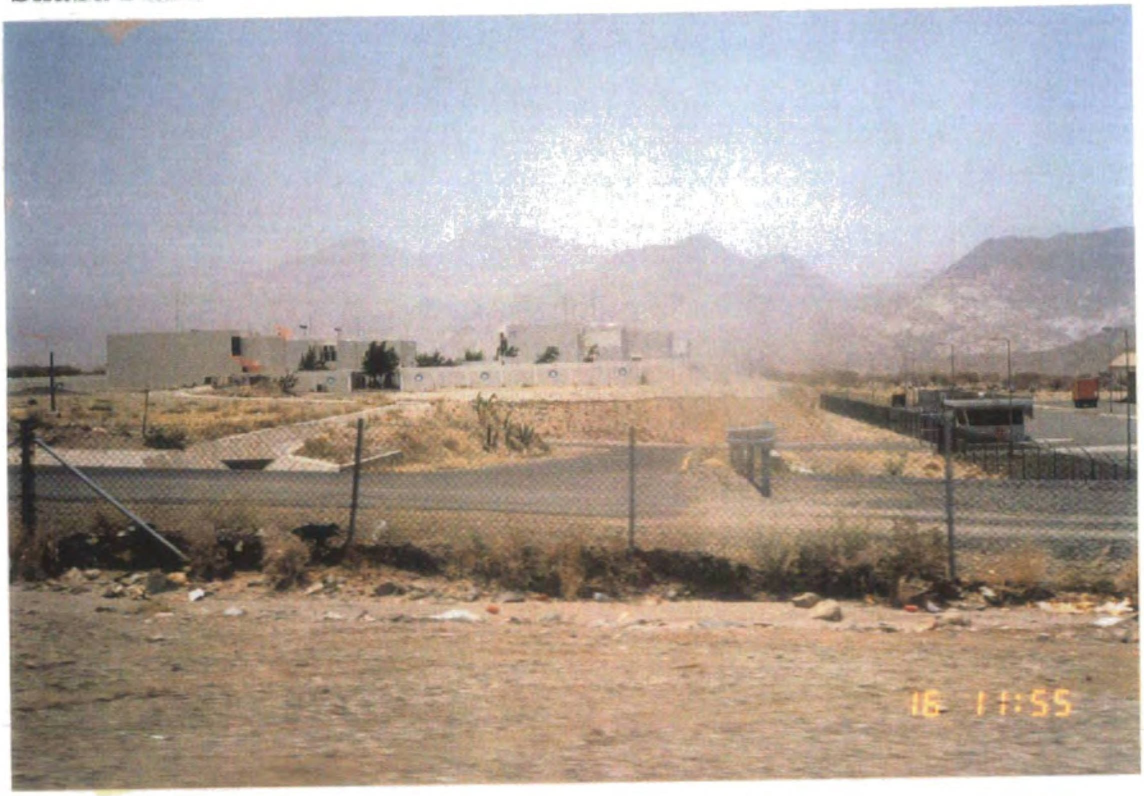
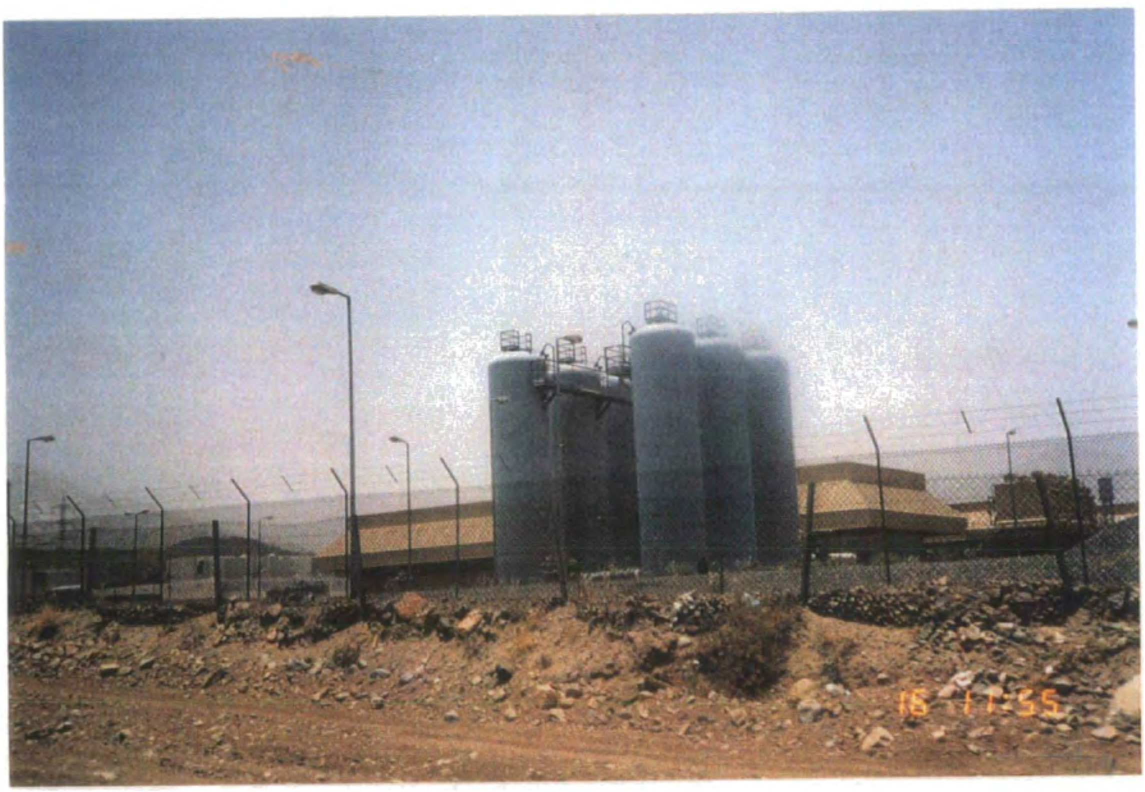


Figure 5.4

Power Pump Station Desalination Pumps Water to Taif From Al-Shaba Plant





water, and has accordingly received worldwide commercial acceptance. The following is a brief description of the industrial process:

a. Incoming sea water is screened to remove suspended material which would otherwise damage the pumps used in the process. The feed is also treated with sodium hypochlorite in order to control biological growth, and then stored in holding tanks for use as required.

b. The process is managed through the use of sophisticated instrumentation for such purposes as controlling flows through various pumps and taking measurements of pressures, temperatures and other parameters throughout the entire system, from the intake through the distillation process and chemical dosing and storage of the product water.

c. Before the sea water enters the distillation process itself, it is treated with chemicals such as polyphosphate to prevent formation of scaling residues inside the condenser tube. It is also used to remove dissolved gases. The sea water feed is then heated to optimum distillation conditions, using steam-heated heat exchange.

d. The MSF process requires many pumps for various purposes such as circulation of brine in the process, discharge of rejected concentrated brine, and moving the product water to the chemical treatment area.

   In addition to the sophisticated instrumentation for process control, there are also controls for fire, hazard warnings and other safety purposes.

   Fuel required to power the multistage flash plants comes from two sources, plants on the Red Sea coast use heavy oil from Petromin's Jeddah Refinery, and plants on the Arabian Gulf coast use natural gas from the Aramco Master Gas System.

e. The product water is treated with such chemicals as chlorine, carbon dioxide and lime in order to make it conform to international specifications for potability. It is then stored in tanks to await distribution as needed.

There are also other methods of producing desalinated water:

Desalination using membrane technology

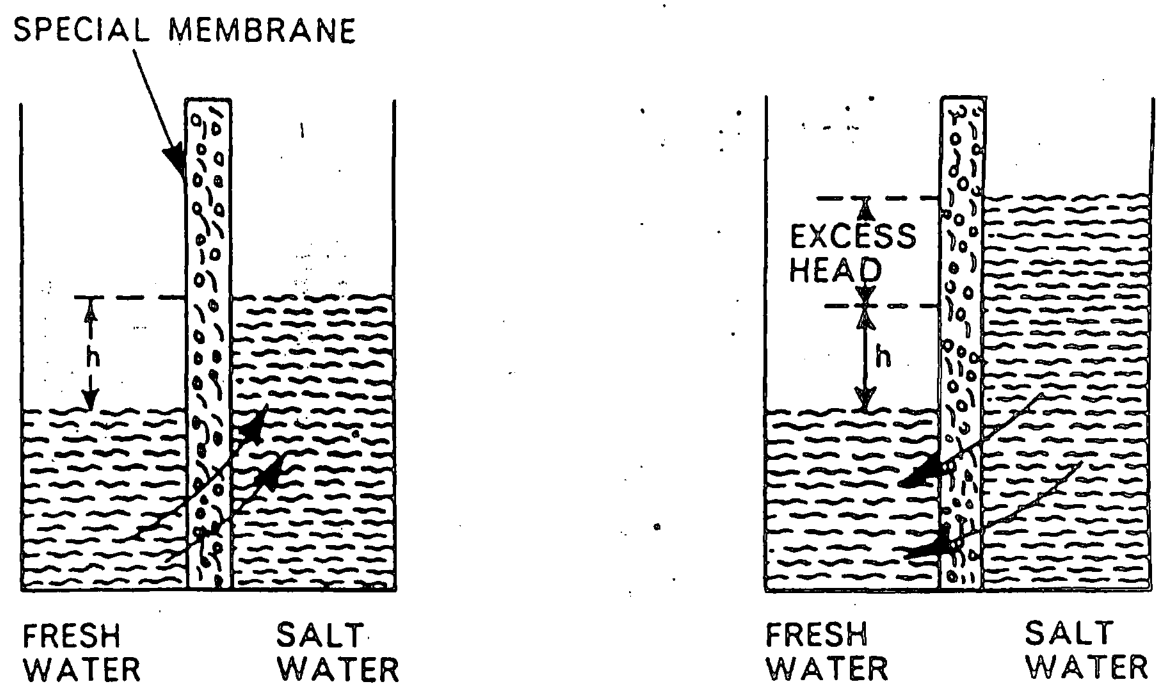
a. Reverse Osmosis

In this process, sea water under pressure is exposed to semipermeable membranes which allow the passage of water but retard the passage of the dissolved salts, thus producing a stream of purified water and a separate stream of more highly concentrated brine. The saline water becomes increasingly diluted until an equilibrium is reached. The increasingly concentrated brine goes back into the sea.

It has directed to eliminating unwanted ions from sea water by mechanical filtration. The osmotic membranes have to withstand great pressure and to pass the water without the unwanted ions. It can easily be seen that such a system would be useless for desalting. All that would happen would be that the saline water would get more dilute until equilibrium was reached. The pressure that causes the water movement is osmotic pressure. Now if a reverse pressure bigger than the osmotic pressure is applied, the water in the saline solution will go the other way into the water. Thus, the water increases and the saline solution gets more concentrated (Figure 5.5)

The main development effort in reverse osmosis in recent years has been in improving the cellulose acetate membranes and the method of manufacturing them. A tubular support system is more promising for use with dirty feed waters and a more compact system is suitable for sweet water.

Figure 5.5: *Reverse Osmosis*



Osmosis - fresh water flows into the solution to equalize osmotic pressure.

Reverse osmosis - pressure applied to solution to overcome osmotic pressure.

The rate of production of the reverse osmosis process is regulated by the pressure and the ratio of input to output salinity required. The process has shown itself to be suitable for the treatment of river water, and of effluents in appropriate circumstances. It has been applied in the Jeddah project for the treatment of sea water and its use is considered practicable.

b. Electro-dialysis

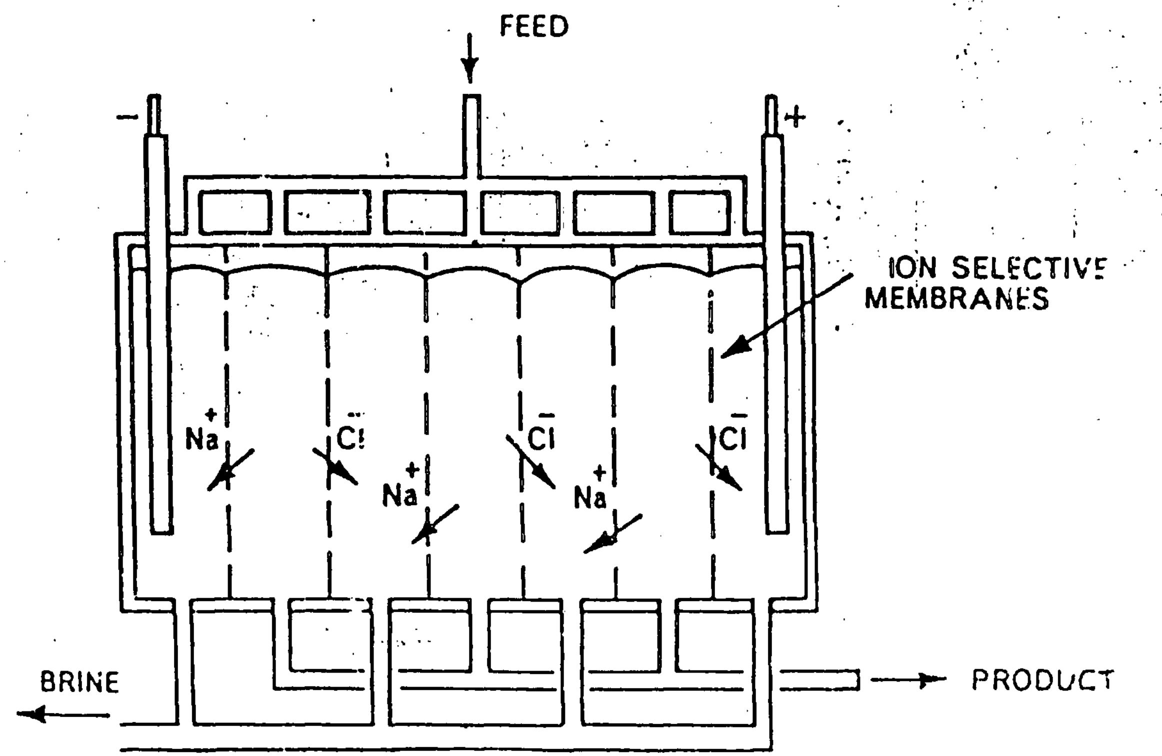
In this process, sea water feed at atmospheric pressure is introduced into cells which contain two different kinds of membranes, one of which permits the passage of positive ions and the other negative ions. Under the influence of an electrical charge, the ions are removed from the sea water to produce a purified product stream and a concentrated brine.

If salt solution is placed between two membranes and an electric voltage is applied across it, then conduction takes place. The negative chlorine ions migrate towards the anode, and the positive sodium ions migrate towards the cathode. Thus salt can be removed from the solution.

In the industrial process, seawater feed at atmospheric pressure is introduced into cells which contain two different kinds of membranes, one of which permits the passage of positive ions and the other negative ions. Under the influence of an electrical charge, the ions are removed from the sea water to produce a purified product stream and a concentrated brine (Figure 5.6).

The method is normally used only for brackish feed water of substantially lower salinity than sea water, since the cost of the product water is directly related to the amount of electrical power consumed, which in turn is proportional to the concentration of salt in the feed water. There are plants in Saudi Arabia, Kuwait, Holland and the US.

Figure 5.6: *Electrodialysis*



c. Desalination by freezing

When sea water is frozen, it becomes possible to separate desalinated ice from brine. The technique makes use of the properties of water solutions already mentioned. It is that of freezing, most of the original work on which has been in Israel. Freezing processes for desalination have been widely studied not least because energy requirements are smaller.

The freezing point of salt water is almost independent of pressure. It is determined by the salt concentration, and varies from 0°C at which temperature pure water freezes, through -2°C at which temperature seawater freezes, down to -4°C at which temperature doubly concentrated sea water (the usual concentration of brine discharged) freezes. Correspondingly lower temperatures apply to higher brine concentrations. By contrast, evaporation of water can take place over a widely varying range of temperatures with the wide range of the vapour-pressure relationship.

Sea water may be evaporated at its freezing point, at a low pressure of about one two hundredth of an atmosphere. The water may be absorbed or condensed in a concentrated solution of a material like lithium bromide, which has a high elevation of boiling point, that is considerable depression of the equilibrium vapour pressure. The solution is boiled to evaporate the water, thus concentrating the solution, which is then cooled for reuse. The ice crystals are separated from the brine, washed to remove a surface film of brine and melted to produce fresh water. Suitable heat exchangers are used.

This method is very simple, and it has the advantage that the latent heat of ice, which is the heat required to melt one gramme of ice, is only 80 calories, just over a seventh of the amount needed for converting water into steam. In practice, one method is to create a vacuum over the salt water. This reduces the temperature and some freezing takes place. The removed vapour is then compressed, which raises its temperature, and it is then brought into contact with the ice crystals which melt and the vapour condenses. Very large amounts of vapour must be dealt with and the vacuum conditions are stringent, hence the capital cost and running costs for the plant are high. This was the principle of the original Israeli process and a plant has been built on the Red Sea to demonstrate its feasibility.

The development of this technology is following this route:

a. There are adequate technical knowledge and confidence to build a complete demonstration plant, which should preferably be of about 500 m^3/d capacity.

b. This would give sufficient experience to enable a 5,000 to 10,000 m^3/d plant to be built.

c. A plant of 22.7 thousand m^3/d capacity would then be possible (see section 5.1-5.3.2).

5.3.2 Development of Sea Water Desalination

Shortage of water not only hinders the expansion of drinking, but is also a great obstacle to industrial development. This lack also restricts urban growth, in several urban areas, groundwater supplies are inadequate for the present population. To overcome this water is problem, the government built desalination plants on the country's coasts, with a production capacity of 628.1 m^3/day.

The sea water desalination plants in KSA have two purposes:

a. to provide additional supplies of water with guaranteed continuous flow;

b. to reduce dependence on ground water which may be insufficient in the future to keep pace with the economic development of the country.

The explosive economic and demographic development of Saudi Arabia has resulted in an increased demand for potable water, a demand which in some places has far exceeded the supply available from local groundwater sources. Since the desalination project was launched in 1965, a large number of desalination plants have been constructed.

Desalinated water is not only used in the absence of groundwater. It is also used where the quality of water is inadequate. For instance, where excessive production from the aquifers causes an inflow of brackish water from the sea, water quality deteriorates. Due to increasing salinity of the groundwater from which towns of the Eastern Region draw their water, it has been found necessary to resort to some desalination. The water so produced is blended with groundwater to produce an acceptable product.

In 1965, after exhaustive studies, Saudi Arabia embarked upon a massive programme of constructing large scale desalination plants for municipal and industrial water supplies.

The KSA has 23 desalination plants on the eastern and western coasts (Arabian Gulf and Red Sea); the total capacity being 503,568,000 m^3 of water per day and 345,475 MW of electricity. The first desalination plant started at Duba and Al-Wajh (see Table 5.1).

The importance of desalination in effectively supplying potable water to Saudi Arabia was further recognised when the government created the Saudi Water Conversion Corporation (SWCC) in 1974. This agency is responsible for controlling and supervising the conversion of saline water from coastal and inland sources.

5.4 SWCC Pipelines

Pipelines deliver water from desalination plants to the cities, e.g. from Jubail on the Arabian Gulf to Riyadh; Yanbu to Medina (175 km); Yanbu to Yanbu City (50 km);

Al-Shuqaiq to Abha in the Asir Mountains; and Al-Shu'aba on the Red Sea to Makkah-Taif in the Hijaz Mountains.

The total length of SWCC's water pipelines for supplying potable water to cities and villages spread out along the Red Sea and Arabian Gulf Coasts, as well as in the interior of the KSA, is about 3,000 km, as shown in Figures 5.7 and 5.8, and the delivery capacity of these pipelines is about 2 mcm/day. This amount of water would be delivered by emptying a reservoir with a depth of two metres and an area of 10^6 m^2.

Some of the desalination plants, both on the Arabian Gulf coast, and on the Red Sea coast, such as Jeddah and Al-Khobar, produce electricity as well as water.

The pipelines are mostly made of spirally or longitudinally welded high quality steel. There are also concrete pipelines (e.g. from Abha to Ahad Rafida). The pipes are lined internally with cement mortar 14 to 19 mm thick and externally coated with polyethylene to a minimum thickness of 3.5 mm. The diameter of pipes varies from 6" to 60", mostly in the middle range. Wider diameter pipes are required to serve the larger cities (e.g. twin 60" diameter pipes run from Al-Jubail to Riyadh; various pipes up to 60" in diameter supply Jeddah with water from its desalination plant). Smaller cities require smaller dimension pipes (e.g. lines feeding the cities of Makkah and Taif vary in diameter between 42" and 56"; the diameter of lines feeding the Eastern Region cities of Al-Khobar, Dammam, Dhahran airport, Qatif, Sihat, Safwa and Rahima range from 16" to 42"). There are also lateral lines to smaller local communities.

Twin lines are laid in two separate, parallel trenches and buried to attain a cover of at least 0.8m. Due to the different soil conditions through which the pipelines pass, different fill materials are used to protect the lines from possible corrosion.

The pumping stations are distributed along the pipelines from the desalination plant to cities, such as Makkah, Taif, Dhahran, Medina, etc.. On twin lines, each station has two identical groups of pumps with each group serving one pipeline, enabling potentially independent operation. The groups are designed so that they may be switched from one line to the other for maximum flexibility.

All pump stations operate with electric power as the most reliable and economic energy source. With the pipeline's great length and output, it has adjustments to handle any operational disturbances. To reduce heavy negative surges generated by sudden system shutdowns, the pipeline automatically directs such surges into safe waiting positions. The flow is measured initially at the intermediate stations and at the terminal to detect any possible leaks along its length. Under normal conditions, however, the pipelines are operated from the plant control centre in the station.

If water is scarce, pressure conduits may be used to avoid loss of water by seepage and evaporation which might occur in open channels. Pressure conduits are preferable for public water supplies because of the reduced opportunity for pollution. Since water engineering deals almost exclusively with turbulent flow in pipes, the pipes must be designed to withstand stresses created by the water flow, and to satisfy the desalination requirements of the plant.

Along the route of a pipeline, a communications cable connects all stations, enabling telecommunications and data transfer. To ensure complete communication coverage, there are eighteen base radio stations along the pipelines to pass information to the control centre.

The examples of pipelines include the following. Water pipelines stretch 102km from Al-Shuqaiq on the Red Sea to Abha. These are steel pipelines, of diameter varying from 36 to 40 inches. There is a double concrete pipeline that stretches 78km with a diameter from 20 to 40 inches. Cities supplied with water are Abha, Khamis Mushayt and Ahad Rafida. Pipelines run from Shuaiba on the Red Sea to Taif: a distance of about 137km. The lines to Makkah (96km) are dual 56 inch diameter steel pipes. The pipeline from Makkah to Taif is a single line 42" in diameter and 41 km in length. As part of the Makkah-Taif pipeline, a 13 km diameter tunnel was cut in Al-Kara Mountain in Al-Huda Region. There are four pumping stations on Shua'aba-Makkah-Taif pipelines to pump the desalination water from plant in Shua'aba to Makkah and Taif across Al-Kara Mountain. There are four water storage tanks in Makkah with a capacity of 50,000 m^3. There are also four tanks in Taif each with a capacity of 25,000 m^3. There are small housing compounds for each pumping station and at the Taif water tank area, as shown in Table 5.2. All the pipelines are used to deliver desalinated water to the local city, or to other regional cities.

Makkah drank from treated sea water for the first time on 21 June 1988 drawn at Al-Shuabia on the Red Sea, 84 km south east of Makkah and 100 km south of Jeddah. This plant came on stream in October 1983 with a daily capacity of 25 million gallons to Makkah and 15 million gallons to Al-Taif. It also generates 325 MW of electricity.

Table 5.2:
SWCC Pipelines

No.	City	To	Distance
1.	Yanbu (a)	Medina	175 km
	Yanbu (b)	Yanbu	50 km
2.	Jubail	Riyadh	465 km
3.	Khobar	Eastern Towns	240 km
4.	Jeddah	Jeddah	46 km
5.	Al-Shuaba	Makkah & Taif	246 km
6.	Al-Shuqiq	Abha-Khamis Mushait	215 km
7.	Jubail	Soder Al-Washim	775 km

After inaugurating the vital Al-Shuaiba desalination plant, the total daily capacity of water supplied by the desalination is more than 500 million gallons and it also generates 3,600 MW of electricity. This plant supplies water to more than 150 cities and villages in the region.

Over the next twenty years, if the rate of population growth remains unchanged, the size of the Saudi population is set to double. So, in the year 2012 water demand will double and new sources will have to be found.

It is apparent that the rapid expansion of the cities is outstripping the continuing efforts to improve water conditions. The current supply of water seems to be only a temporary solution as the cities maintain their rapid growth rate. In order to assure a bright future, the impact of city growth must be considered.

5.5 Desalination in Tihama Asir

The seawater made above are based on several assumptions, and conclusions could be made less stringent were more flexibility introduced into the system. The result would be the release of some of the safety reserve of 9.4 mcm for agriculture. However, for the time being, since some uncertainty exists on the level of underground water resources, their fluctuation with time, and on the actual demand of population centres, this approach seems sufficient.

Desalination will not be introduced before 1995. When it is, it should account for all additional urban demand, thus leaving constant resources to agriculture. The urban supply from the underground aquifer in Jizan, Sabya and Abu Arish area should be maintained in the long term at its 1985 level. A safety margin should, however, be kept to account for discontinuities in the development of new resources such as desalination.

Tihama Asir region has been divided into four water resources areas, independent hydrologically, and consequently if demand exceeds supply within either one, the deficit will have to be filled by transferring water between surplus and deficit areas or by desalination. If a dam's useful life is 30 years (dams progressively fill with alluvium), the cost of the additional m^3 would be approximately 5 SR (about 1 US $), which puts it on the same level as desalination. This is why desalination will be a valuable way of bridging water deficits.

Tihama Asir is an agricultural area with demand for water divided between domestic and agricultural use. The population served by each watershed is small, as the area does not have a large population. In addition to the agricultural dimension of fields and farm buildings, the are also has some industry within small towns and villages. All these reasons have left the area to use natural water during this period. In the future, once the area is more developed and with increasing population, desalinated water will be used. The government plans that 1995-1996 will see a production capacity of 7.9 mcm/year and will increase to 17.3 mcm by the year 2000.

5.6 Recycling

Water reuse refers to the use of waste water or reclaimed water. Water reclamation refers to an upgrading of the quality of water to make it usable again. The exact nature of reuse remains unclear. The treatment of waste water and the method or manner by which the waste water reaches the next user are critical to the feasibility and desirability of reuse. Inadvertent reuse occurs when water is withdrawn, used by one party, returned to a water source without specific intention or planning to provide the water for the use of other parties, but is nevertheless so used. No natural buffers, such as lakes, rivers or groundwater, serve as intermediaries to expose the waste water to natural purification and dilution systems, for example, Riyadh at Al-Haiyer area (Figure 5.9).

The reuse of domestic and industrial waste water in Saudi Arabia is very limited. This is partly due to poorly developed sewage collection systems.

Reuse (waste water) that is discharged and then withdrawn by a user other than the discharger (Al-Marshoud and Jared, 1982), and the recycling as the internal use of water by the original user prior to discharge to a treatment system or other point of disposal, and a series of two or more consumptive users that occur due to the acts of man, in which a portion or all of the water originating from the first use, and then used a second time, has not passed through and unconfined gaseous state between uses (As Suqqir, 1982).

For the purposes of this study, waste water reclamation is defined as: the use of advanced waste water treatment scheme to render wastewater reusable. Reuse is defined as the utilisation of water than has been used previously. A breakdown of these terms reveals that the water user, water use (purpose), and planning intent are at the heart of every reuse contextual framework.

The system may be defined by hydrologic boundaries, such as a river basin, or by administrative boundaries determined by the jurisdiction of the planning authority. The system may be large or small, and may be considered at various levels of aggregation are complimentary. Large systems necessarily require a higher level of aggregation than smaller ones if the number of variables considered in the planning process is to be manageable. Water and water- related actions, projects and programs affect all people in some way or another. They often have substantial effects on a person's life, especially on the quality of his and on his economic condition. Water projects can induce, directly or indirectly, a large number of changes in the environment, some of which cannot be adequately predicted.

To conserve precious water resources, irrigation water for landscaping is obtained by reclaiming sanitary waste water. Industrial waste water is also reclaimed for industrial water use and fire-fighting needs.

Waste water is any water derived from one or more previous uses. It may be supplied untreated, or collected and treated for some additional water use. Treatment processes renders the water suitable either for discharge or for reuse.

Throughout Saudi Arabia water treatment plants are being constructed to treat the growing volume of domestic waste water. After undergoing biological and chemical treatment, the water is then used for irrigation, garden and park watering, and air conditioning systems, as in Figure 5.9. For example, a plant near Riyadh is used for agricultural purposes, pool for connected sewage to distribution of irrigation water to farms..

It is important here to review the possible health risks associated with various forms of water reuse in agriculture. The degree of risk involved may vary greatly. Such reuse may be directed solely to the irrigation of industrial or other crops not for direct human consumption, or, on the other hand, it may involve highly health sensitive crops such as fruits or vegetables that are generally consumed uncooked. In either case, the health risks to agricultural workers must be evaluated as well as the possible dispersion of aerosolised pathogens by spray irrigation in the vicinity of residential areas.

The utilisation of waste water in Saudi Arabia has been considered by the MAW for almost three decades. The water authorities recognised the importance of collecting and treating the effluent to be used for various purposes such as irrigation, industry, recreation and groundwater recharge. Such utilisation would lessen the pressure on the natural fresh water supply, conserving it for more valuable uses.

The reclamation of waste water is in its early stages of development in Saudi Arabia and requires extensive treatment and control in accordance with strict water quality standards. Advances in treatment technology and the improvement of sewerage

Figure 5.7: *Desalination plants and pipelines in KSA*

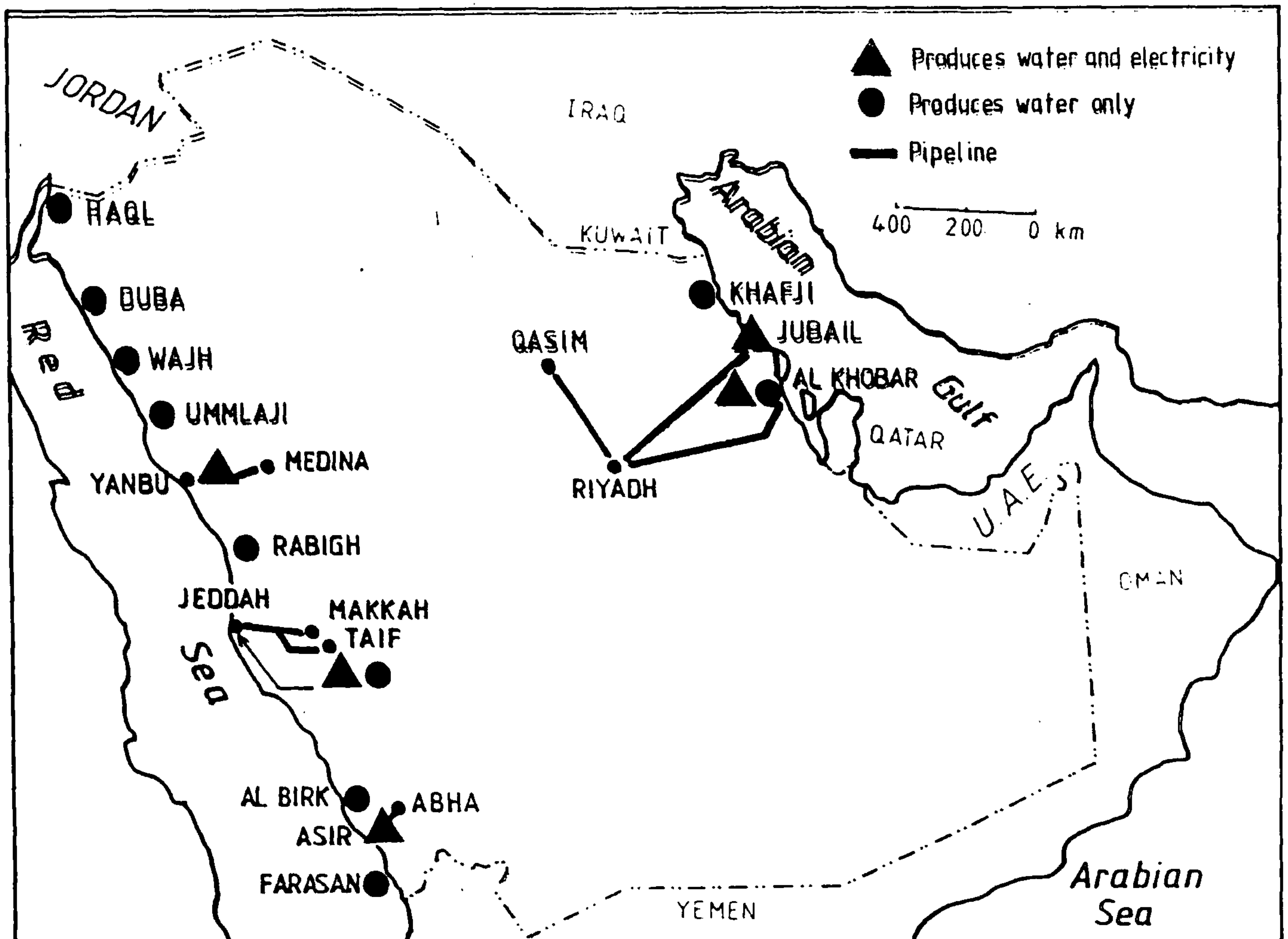


Figure 5.8:

The Pipeline extends from the Desalination Plant to Jeddah City

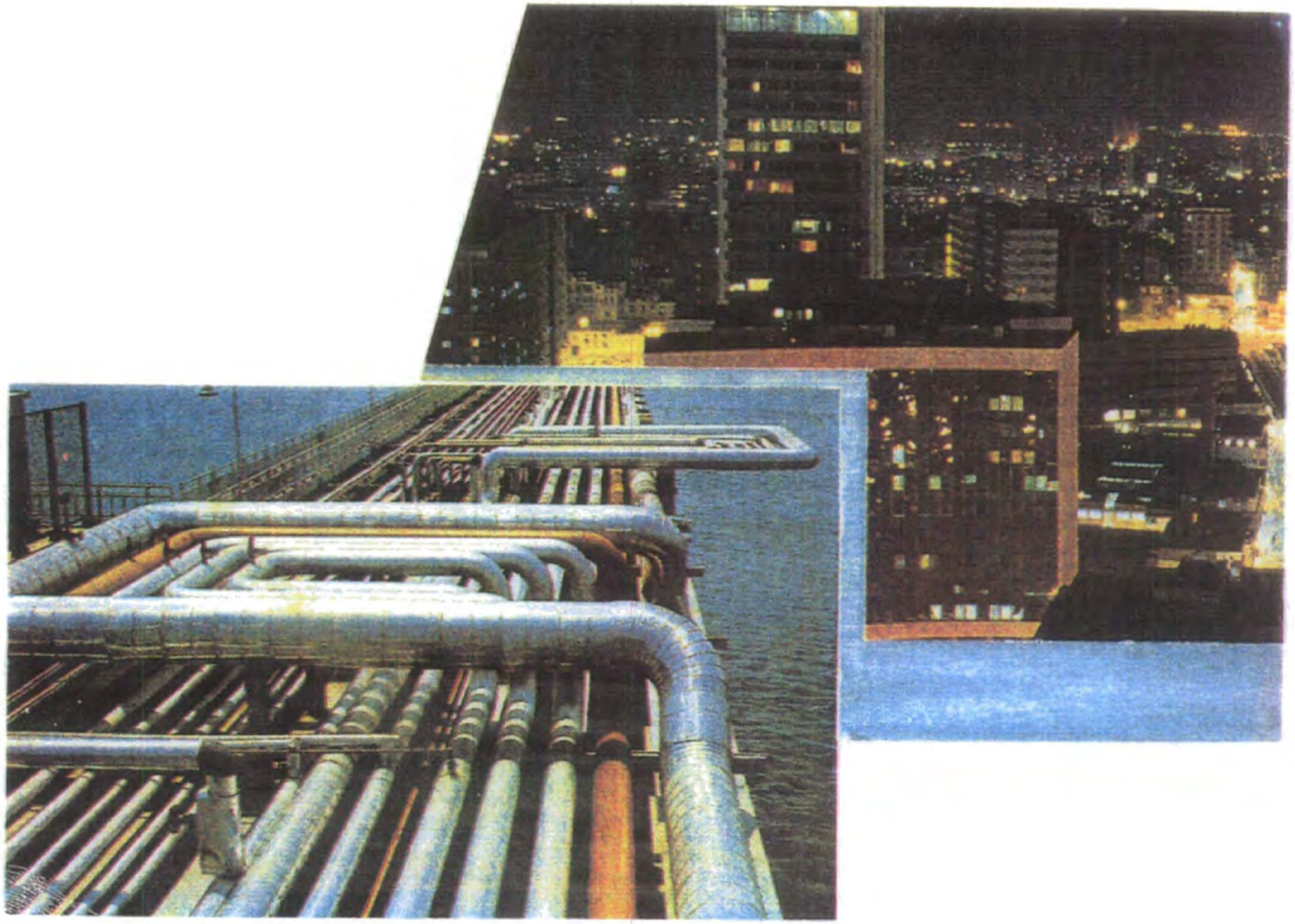
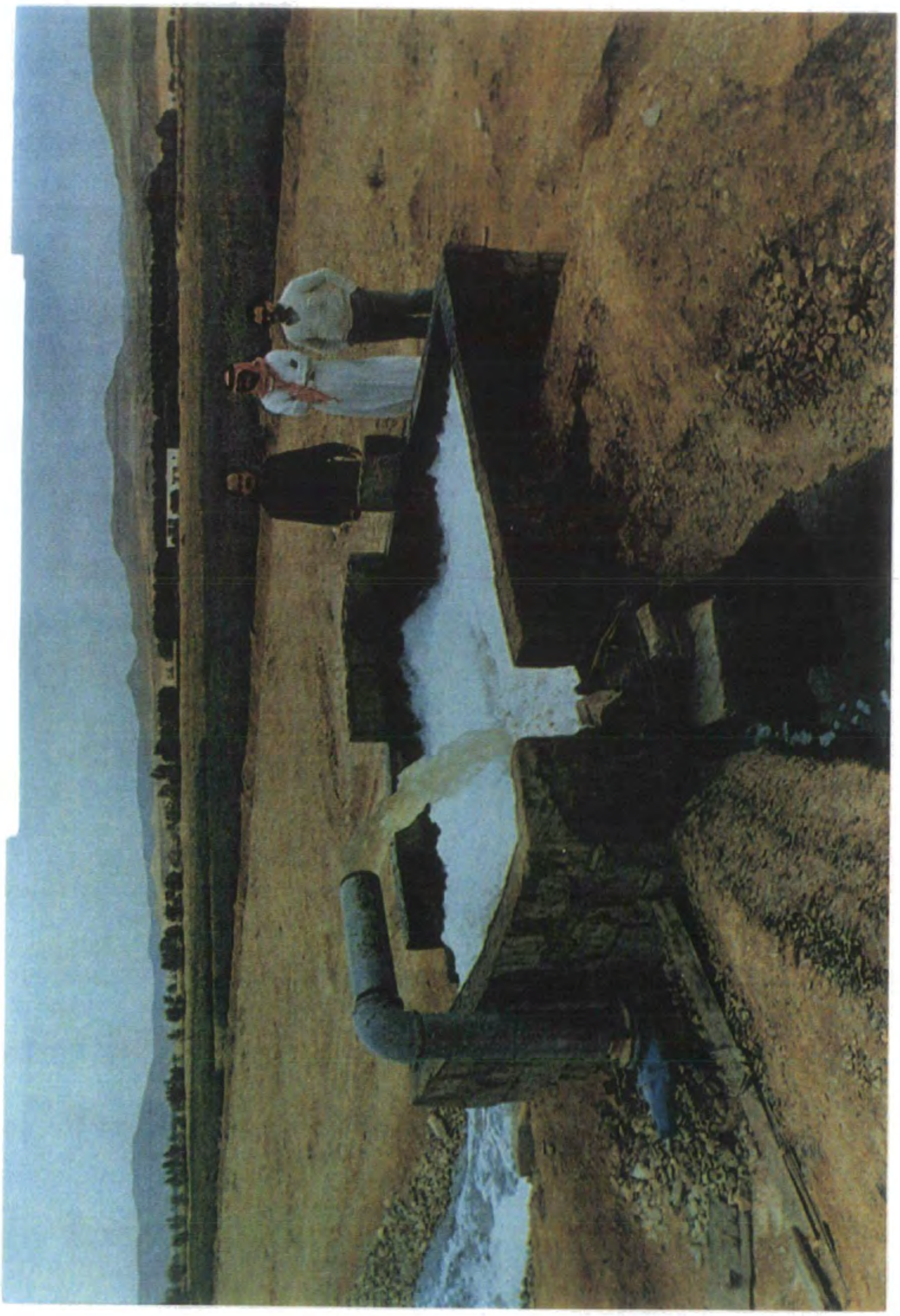


Figure 5.9: *Sewage water pumped for irrigation*



networks have resulted in the ability to use this resource for irrigation, landscaping and industrial uses, though not for human consumption.

Nevertheless, apart from the image problem, there remains the real risk of unknown health hazards associated with treated sewage. Treatment lowers the risk, and improves the quality from one level to another.

There are four principal reasons for the collection and use sewage in Saudi Arabia (MAW, Department of Water Development, 1989):

1. For irrigation, high government priorities since fresh, natural water is scarce and valuable.
2. To avoid potential health hazards and to protect city water pipes and public and private buildings from damage from sewage pipes.
3. To prevent possible contamination of nearby shallow aquifers.
4. To dispose of the effluent because no natural discharge area exists, such as a river, lake or sea. Reuse of treated effluent provides a means of discharge.

Waste water will ultimately be replaced, of course, but only through the hydrological cycle over which we have at present little control. Farmers are thus continually faced with the problem of capturing and conserving enough water for their needs, especially in drier regions.

5.6.1 Sewage Recycling in the Water Problem

To conserve water resources, irrigation water for landscaping is obtained by reclaiming sanitary waste water. Industrial waste water is also reclaimed for industrial water use.

Treated sewage water is one of the sources that has an important role in meeting a substantial portion of agriculture, industry and recreation sectors. If this water is not available for these uses, it becomes necessary to draw water from the groundwater intended for domestic purposes. The Ministry of Agriculture and Water (MAW) carried out several projects to convey treated sewage water to Dirab, Dereya, Erga, Al-Ammareya and Mayer for agricultural purposes. The water is taken from Riyadh Sewage Treatment Plant with a capacity of 2,000,000 m^3/day. Also 20,000 m^3/day are utilised for industrial purposes where Petromin refinery gets the use of it. The success in this field and good results achieved encouraged the reapplication of sewage water in other towns such as Medina, Qasim, Jeddah and East Province.

Whilst this development does have the potential for providing extensive supplies of water to agriculture, so far only limited progress has been made due mainly to weaknesses in the treatment processes which have led to doubt being cast by some on the suitability of treated water for agriculture.

The results of an experimental study in which carbon chloroform extract (CCE) of water suspected of causing cancer in humans were injected into mice, produced no evidence of carcinogenic properties in the water. This suggests that one possible explanation for the inconclusive results is that some of the potential carcinogenic elements that may have been polluting the water were not absorbed on activated carbon.

The application of manure to agricultural land has been widely practised in the Far East for many centuries. The reuse of municipal waste water for agricultural irrigation is one of the oldest forms of water reclamation. At the end of the last century, major land irrigation projects were developed in Germany and in England. It should be pointed out, however, that the primary motivation of these early projects was essentially treatment and disposal of municipal waste water, rather than water conservation and recycling. Figure 5.9 also shows a motor pump being used to irrigate land using sewage water pumped from the outflow of Al-Hayer treatment plant in the Riyadh area.

Reuse could delay or obviate the need for conventional additions to supply by providing 1) a substitute for high levels of assurance of reliability of supply; 2) a method of mobilising over-supply resulting from the understatement yield; and 3) a method of shortening the planning horizon to allow the pragmatic evaluation of change in demand to replace the present long term projections.

Water management requires extra effort to maximise benefits in regions of scarce or expensive water supplies.

Promising supply and demand management technologies exist to play a role in supplying needed water. One supply technology, reusing reclaimed water, is a potentially attractive choice to augment existing water supplies and is the focus of this research. Some of the parameters motivating wastewater reclamation and reuse decisions are:

Inadequate natural supplies and/or quality of water; conservation of available resources through recycling (for example, recycling water used by industry frees fresh water for other uses demanding higher quality, such as drinking water); the under-exploitation of agricultural potential in arid lands; the availability of treatment technology to allow efficient reclamation of almost any type of waste water. Some general considerations affecting water reuse decisions include: local water supply conditions; water quality requirements for various water reuse applications; the degree of existing or proposed waste water treatment facilities and process reliability; socio-economic and cultural acceptability; and the capacity to mitigate potential health risks (Hammer, 1986).

5.7 Water Supply and Sewage Networks

In most cities that reuse their water, the sewage department controls a completely separate water renovation and distribution system. A more flexible alternative is to place control in the water department and provide a method of interchange so that either water from the potable system or renovated effluent could serve non-potable uses.

Consequently, if the large quantities of generated agricultural drainage water were recycled, they could become a major source or water in Saudi Arabia. That the amount of drainage water generated by the Al-Hasal Irrigation Project varies from approximately 132,000m^3 of water per day in the summer to almost 570,000m^3 of water per day in the winter. The cost of reducing salt content of this water from over 4,000ppm to less than 1,000ppm (TDS) is about 52/m^3 (MAW). Therefore, the findings of the study are very encouraging since up to 3,800ha of farm land could be cultivated with the reclaimed water.

5.7.1 Sewage Treatment Process

Industrial and residential waste water generally contains a variety of organic and inorganic matter that must be removed or greatly reduced before water is re-used.

Industrial units ordinarily discharge their waste water into a city's sewage system after pretreatment. In join processing of waste water, the majority of manufacturing wastes are most amenable to biological treatment after dilution with domestic waste water. However, a large volume of high-strength wastes must be considered in sizing of municipal treatment plant. Certain industrial discharges, such as dairy wastes, can be more easily reduced in strength by treatment in their concentrated form at the industrial site. If re-use of the waste water is planned, rather stringent controls on industrial discharges are needed, since many of the substances in manufacturing wastes are refractory, and conventional treatment and will interfere with water re-use. In a city, the major waste water contributors are food processing industries. The manufacturing of waste water from rubber products, metal working and carpet weaving have strengths comparable to domestic waste water. Therefore, the quantity and strength can be related to the number of persons that would be required to contribute an equivalent quantity of waste water. In addition to equivalent populations, it is desirable to express the quantity of waste water produced per unit of raw material processes.

Industry generally requires large amounts of water for cooling, and lesser amounts for processing. For example, on average, nearly 93% of the water used by industry in the United States is deposited back into natural streams, while only 7% is consumed.

In 1976, Dove reported that industrial requirements for water in Saudi Arabia are expected to increase dramatically. For the purpose of meeting the anticipated needs related to industrial expansion and development, greater amounts of water must be made available. The cement industry, for example, accepts water of poor quality because the suspended solids in the water usually melt and mix with the cement compounds during processing. By contrast, the paper industry requires water of high quality because even small amounts of minerals such as iron or manganese affects colour purity.

In 1980, the General Petroleum and Minerals Organisation (Petromin) began using effluent from the Riyadh waste water treatment plant and reclaiming it for use in the refining process is nearly 20% of used water for industry in Saudi Arabia, and for agricultural irrigation nearly 10%.

In many countries, the reuse of treated effluent is common. The Bethlehem Steel Plant near Baltimore uses treated water for cooling. The smelting iron industry in England consumes approximately 18,000 m^3/day. At present, Riyadh Oil Refinery uses nearly 20,000 m^3/day for cooling.

Reuse possibilities must be considered in various industries in an effort to reduce water consumption in a fast growing industrial city. Water conservation and reuse possibilities were assessed by the MWA.

The sewage is intended to supply water to each factory, but a few problems still remain unsolved. Further studies on ways to improve quality by using active carbon treatment are now in progress.

The recent improvement in sewage systems has eliminated the intrusion of sea water and diminished the salt content in sewage to 100 ppm or less.

A qualitative presentation of the current problems can be summarised as follows:

(a) An increase in chloride ions due to the intrusion of sea water causes troublesome scale and metallic corrosion.

(b) Ammonia included usually 8-10 ppm as NH_4NO_3 causes corrosion of alloyed copper (MAW).

The function of sewage treatment plants is to separate organic material and inorganic solids from water. After being collected and delivered to the treatment plant, the sewage effluent undergoes two major steps: Primary and Secondary Treatment.

Primary treatment is mainly a mechanical process that consists of screening and sedimentation mechanisms. Before any type of treatment can be done, the suspended and floating matter, such as rags, wood, paper and metal cans must first be screened out to prevent the channels, pipes and valves from being blocked and to protect plant equipment from damage.

Secondary treatment, by contrast, is a biological process which uses either activated sludge or trickling filters. Activated sludge is a process that increases the bacteria interaction in the sewage by adjusting the needed biochemical oxygen demand (BOD) with bacteria to oxidise and convert organic into inorganic matter. Eventually suspended matter coagulates and settles to the bottom of the sedimentation tanks.

A third treatment to further reduce remaining matter is used if a higher quality reclaimed sewage water is required. This advanced stage of the treatment process allows the liquid waste to flow down a graded slope. As the effluent runs downhill, the organic and inorganic matter interacts with the soil and its vegetative cover, screening out and neutralising both components of the sewage.

By the end of the second and third treatment steps, the water is clean, but still contains various micro-organisms such as viruses and harmful bacteria. Therefore, chlorine and ozone are frequently used as disinfectants (Figure 5.10 a and b).

5.7.2 Development of a Recycling Programme

The Saudi Arabian urban dweller has access to modern water supply systems. In 1970 supply and collection networks were being augmented by municipal sewage waste water treatment facilities in response to the emergent concept of waste water as a water supply resource. Figure 5.11 represents a projection of water uses 20 years planning horizon which was largely based on a revision of water demand. Industrial water demand is not identified separately in most relevant publications. It was quantified here as about 52% of published municipal use, in line with experiences in the country. The projection for waste water was based on a summation of all existing and planned treatment plants, which appeared to be a little higher for domestic use than other resources. The agricultural irrigation is in the absence of any serious effort in the direction of the resource being eliminated. In 1981 sewage treatment plants were already in operation in some cities such as Riyadh, Madinah, Jeddah, Khobar, Dammam, Buraydah, Taif and Hasa. Figures 5.12 a & b show pipelines carrying the re-used water for domestic use in Taif. Offers a projection of water uses for different

Figure 5.10a:

Al-Hayer Treatment Plant in Riyadh

Figure 5.10b:

River from Sewage Water at Al-Hayer near Ritadh

Figure 5.11:

Projections of Water Resources Utilization

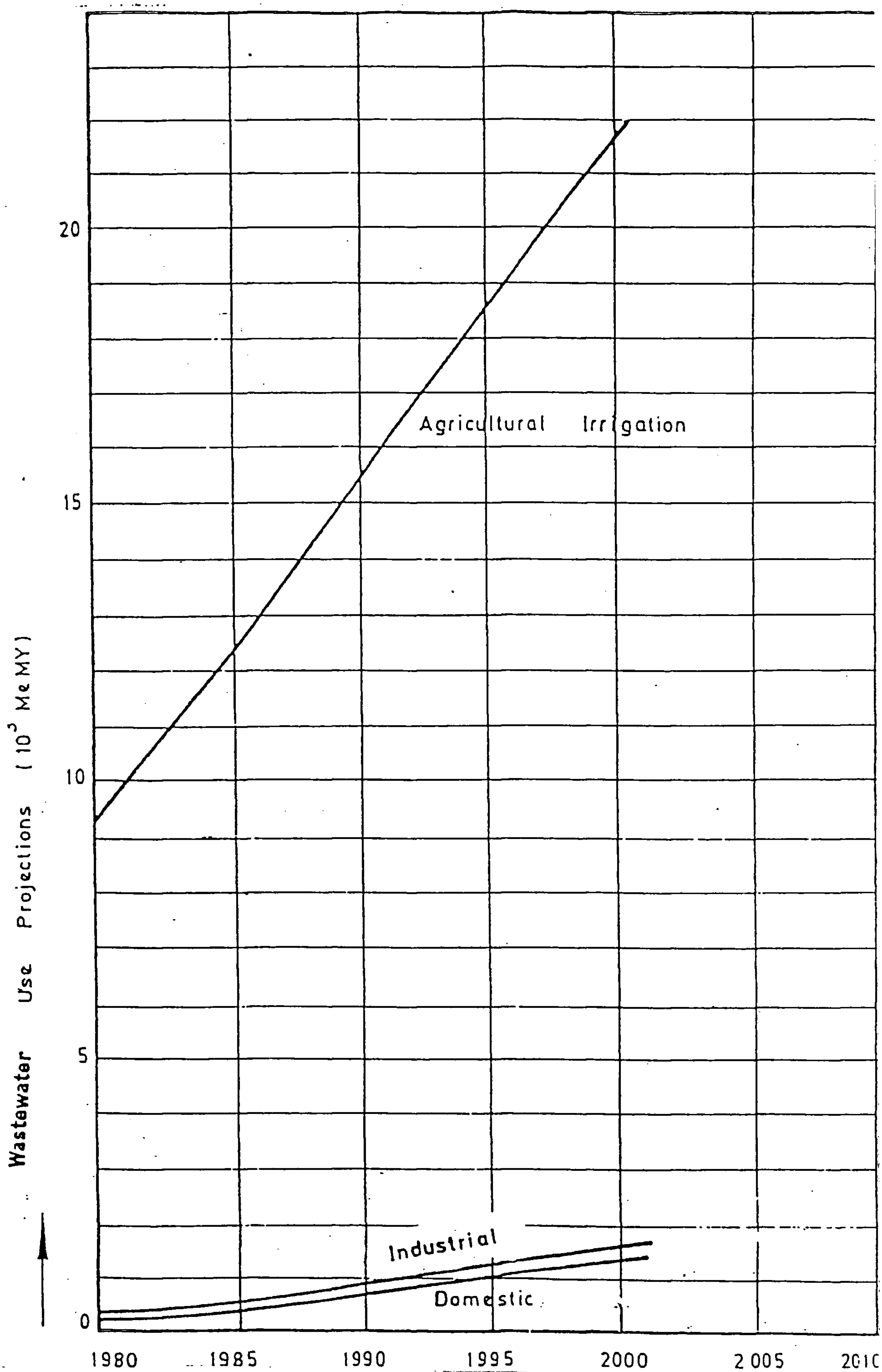
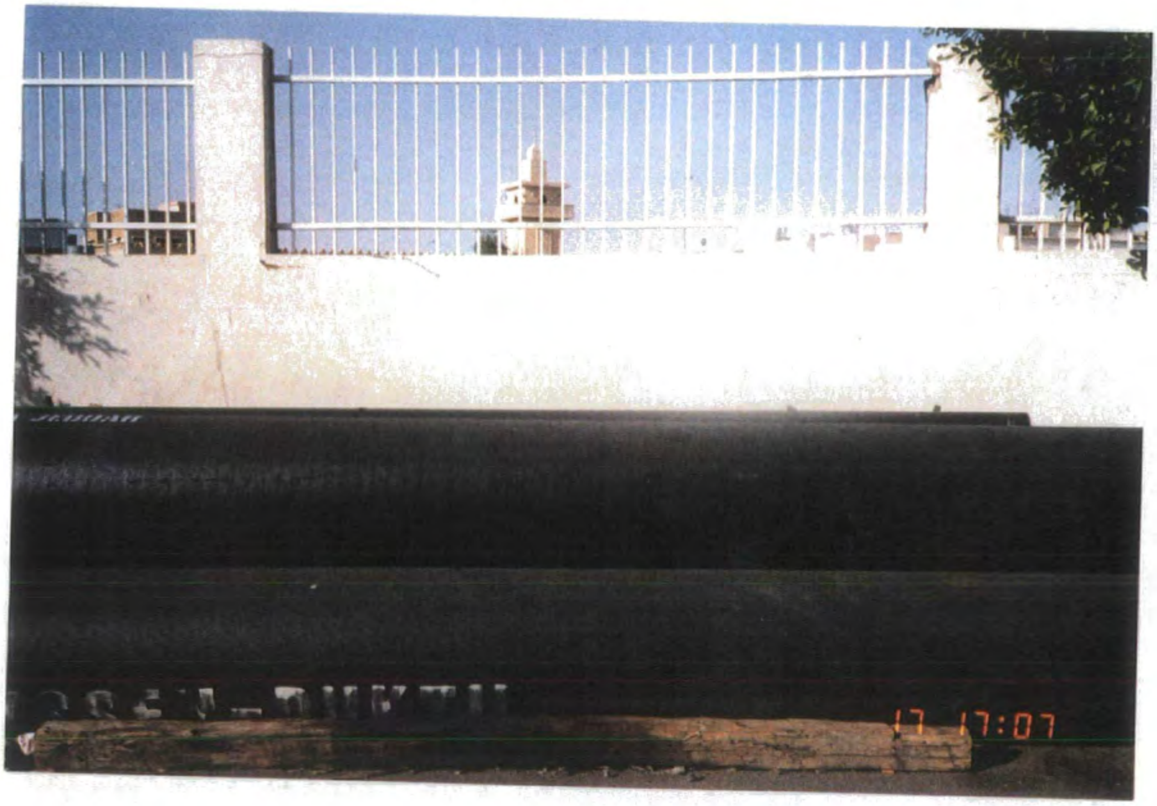


Figure 5.12a:

Network Distribution uses Sewage Water in Taif

Figure 5.12b:

Pipelines used for distribution of sewage water



types: domestic, industrial and agricultural irrigation in the country. This strategy is based on using waste water to the fullest extent which existing facilities allow. Domestic and industrial uses are shown as the smallest waste water uses, perhaps because it is a new source. Agricultural irrigation will, in future, make good use of waste water for those uses that in the past used waste water without filtration. Throughout Saudi Arabia, approximately 100 mcm/y of waste water is used.

The Riyadh Treatment Plant expected that in the years 1990 and 1995 a total of 40,000 and 600,000 cubic m/day respectively would be made available from the pilot plants for reuse in and around Al-Riyadh, 100,000 m^3/day was used for irrigation and recharge to aquifers and another 100,000 m^3/day was used for industrial and recreational sectors (MAW).

The waste water is a more recent supply of water in Saudi Arabia. It is blended with brackish groundwater to be used for agricultural irrigation. The waste water will supply around 100 mcm/year of water to agricultural irrigation, limited domestic use and industrial use near large cities (MAW).

The objective of the treatment project is to treat a secondary effluent from the existing sewage works and producing a final water of a suitable standard such that it can be used for irrigation and domestic use, but will not be injurious to human health if consumed in any quantity.

The design of the treatment project has been based on flows given at the tendering stage and or, an average analysis derived from samples collected on the 18 August, 3 and 14 November 1981, and analysed in Ames Crosta Babcock's laboratory in Heywood (A. Babcock International Company), together with recorded data from the sewage works covering the period 30 May to 5 June 1981 inclusive.

The municipal treatment plants were based on biological filters, or on activated sludge systems or oxidation ponds. However, in order to meet the higher standards required by MAW multi-purpose re-use plants, recommendations were made to employ such advanced waste water treatment technology as sand filtration, denitrification, flocculation, phosphate removal and disinfection. It was determined that one of or a combination of the foregoing systems would be needed depending upon the type of re-use specified for the treated waste water.

Much more sophisticated treatment processes are used to reduce heavy metals and toxic elements before it can meet the standards required for discharge into municipal waste water treatment before re-use.

This system is referred to by a variety of methods. This treatment has been specifically developed to remove suspended solids, biodegradable organics and micro-organisms. from waste water.

Although, in many locations, the effective treatment systems are constructed. Therefore a short description of this system and the treatment which it can provide is given.

As illustrated, waste water undergoes preliminary treatment. This is to protect downstream pump and pipes from harm from large articles and abrasives which were often found in sewage. Sedimentation is provided to remove relatively large organic solids. Such treatment is referred to as primary treatment. In the case of municipal waste water, only about one third of the oxygen-demanding materials are removed by primary treatment. Bacteria and viruses are partially removed by silting.

Waste water effluents from municipal plants using primary treatment can be used for irrigation of crops, but not for direct human consumption.

Most sewage water is for non-potable purposes supplied directly from the treatment plant to the user. This category includes most of the present uses for irrigation, industry and recreation. Water sewage is a major element of national policy with pressures of growing demand upon extent water supplies.

The use of purified sewage effluent is of agricultural importance, especially in the poorer areas (see the desalination in the water problem in this chapter.

It is plain that in Saudi Arabia as in many other areas of the world recycling and reuse of all resources will have to become a way of life.

The network of waste water treatment plants in urban area is incomplete because renovated water use is still in its infancy. A small amount of treated waste water is used in big cities to irrigate public gardens and to supply some industries with cooling water, while a considerable proportion of waste water is either discharged into the sea, or treated and used in refineries and by agriculture.

Substantial progress has been made in the provision of water treatment resources in Saudi Arabia, and indeed the first major scheme is the Al-Riyadh Sewage Scheme. This first water treatment plant, the bulk of which was constructed in 1979, now serves a population of more than 10,000,000 throughout Al-Riyadh, although only 80% of the city centre is connected to the system owing to similar kinds of problems as those experienced in Dirab, Al-Dariyah, Arrikah and Al-Ammariyadh for irrigation.

The focus of the system is the Al-Riyadh sewage works which has a capacity for treatment more than 300,000 m^3/day, of this treated effluent is pumped to an experimental farm at Dirab. 60,000 m^3/day is pumped to various production farms at Al-Dariyah. 60,000 m^3/day, to Al-Ammariyah, 20,000 m^3/day and 20,000 m^3/day to Arrikah (MAW).

The oil refinery in Riyadh used 100,000 m^3/day of sewage water and a city forestation area used 20,000 m^3/day. This will be supplied to some extent by installing a tertiary treatment system at Al-Riyadh involving rapid sand filtration with pre- and post-chlorination (MAW).

Makkah and Taif sewage treatment, the largest project consists of an operation and maintenance for these cities' sewage treatment, recycling and drainage networks.

The Makkah sewage treatment plant, which has a capacity for treating 10,000 m^3/day, was constructed south of Makkah in 1975. Eventually, it became necessary to increase the plant's capacity to accommodate the rapid expansion of the city sewage network. For this reason, an agreement was made in two stages; the first stage would raise it to 40,000 m^3/day, the second to 140,000 m^3 (MAW).

The Makkah plant, like most other sewage treatment plants, consists of a screening section, four grit removal tanks with eighteen pipe columns in each for aeration, four primary sedimentation tanks, and four sludge digesters. After the sludge, a byproduct, is dried on 30 drying beds, it becomes a fertiliser prized by local farmers as an excellent soil conditioner. Methane gas, which can be used as fuel, and carbon dioxide are also byproducts of the digesters.

Jeddah treatment plant has two treatments, one in southern Jeddah and the other in the north east of Jeddah. The treatment serves a population of about 1,200,000, although only 50-60% of the city centre is connected to the system owing to similar kinds of problems as those experienced in Riyadh.

The system is the city sewage works which has a capacity for treatment of 60,000 m^3/day. Of this, 20,000 m^3/day of treated effluent is pumped to an experimental farm north east and east of the city, 40,000 m^3/day is pumped to various production farms and the remainder is pumped into the Red Sea (MAW).

In the Tabuk, a waste-water system, the project includes a water treatment plant, pumping station and pipeline, to expand the sewage system in the town of Shihat.

There are many advantages of waste water reclamation:

1. The increased potential for irrigating more land by using the assessment of the domestic and industrial water consumption of the country, and assuming that 50% of the domestic water is recoverable, the amount of water reclaimed annually would be 250mcm. Irrigated land could therefore increase by 24,851 ha (10,100m^3 of water/ha average for Saudi Arabia). Because this source of water continues to increase each year, the amount of land that could be irrigated would also increase. The reclaimed waste water could be used for irrigating soils, stabilising plants, for growing fodder, seedcrops, and other crops which require cooking before they can be consumed, and for landscape irrigation.

2. Increased industrial use, the possibilities of using reclaimed waste water for industrial purposes are unlimited, one way of utilising this water would be for heating and cooling, which uses large volumes of water. Another possible use of reclaimed water would be for oil fields injections, rather than exploiting non-renewable groundwater sources of using the expensive desalinated seawater.

3. Provision of nutrients, because reclaimed waste water is high in nitrogen and phosphorus, farmers would benefit from its use in irrigation by saving the money they would normally spend for fertilisers.

4. Production of sludge residue, that remains after the reclamation process is rich in nutrients and makes an excellent soil conditioner.

5. Convenient location. Reclaimed waste water plants may be located wherever people settle, while coastlines are the only possible locations for desalination plants.

6. Pollution control. Waste water reuse would solve the problem of unregulated sewage which could pollute Saudi Arabia's environment. In addition, this unregulated sewage provides a breeding ground for a host of parasitic diseases (MAW).

5.8 Sewage and water treatment in Tihama Asir

A sewage system is definitely necessary and important to improve hygienic conditions of the Tihama Asir area. There is no sewage pipe system in the area. In the cities, many houses have cesspools, and the municipalities carry out sewage collection services by tank rolly from the cesspools. However, they dispose of the sewage directly onto the ground without treating it. In Jizan, the planning for the sewage pipe system is now underway.

The almost complete absence of urban sanitary networks has created many problems which are expected to magnify as the water supply expands in the cities areas. The problems are:

a. The pollution of the underground water-table, with possible contamination of non-pressurised potable water systems and sanitary hazards for irrigation from tube-wells.

b. The creation of permanent stagnant pools in low-lying areas which are unpleasant and conducive to the breeding of mosquitoes (malaria), as well as a hazard to animals.

In view of the existing conditions, sewage should be a priority sector. The general objectives for sewage are:

1. Improvement of sanitary conditions.
2. Water recycling.

Since the construction of sewage systems is costly and time consuming, the emphasis in the short term is placed on cities, sewage systems in rural service centres would be provided later on.

The expected sewage flow will increase as water consumption is augmented in cities and towns. At first, development stage oxidation ponds, which are very simple and efficient under the climatic conditions of Tihama plain, are proposed when sites and soil conditions are suitable. At later stages, because of the need for better quality effluent for re-use in agriculture and industry, avoidance and evaporation losses and for space reasons activated sludge sewage treatment plants could be introduced. Although, the sewage flow collected in 1990 was 10,700 m^3/day compared to three times this rate in 1995, the construction effort in 1990 would be most important, because it involves the supply of the main collection and treatment plants in the five cities.

5.10 Artificial Supplies in the Future

The domestic and agricultural sectors of society in Saudi Arabia could experience severe water deficiencies in the coming years.

Desalination does not hold the answers to all the water problems of Saudi Arabia. Unfortunately the essence of the problem would seem to be that the government appears to believe that it does, hoping that new supply developments can reduce costs and increase output. As, however, such developments are by no means guaranteed, it is argued that any government which sees desalinated methods as providing the bulk of future water supplies, at least for domestic and agriculture uses, could be jeopardising future development.

Many possibilities do exist to increase urban water supplies, and many new, non-natural supplies of water from desalination and recycling are being used extensively. However, many of the new approaches and supplies of water could yet experience problems.

The essence of the problem is, therefore, the fact that the high level of development which is planned very much depends on the provision of large quantities of water.

Research into new sources of water must continue but this must be carried out in association with a far greater appreciation of the long term consequences and demand, in order that sound and realistic programmes of economic and water resource development might emerge and prove viable well into the next century.

Indeed, Saudi Arabia is already, for instance, beginning to cut back on the number of desalination contracts it puts out to tender, for reasons of economy at the very time when many see desalinated water as providing the bulk of future domestic water supplies.

The technology of desalination has been progressing and probably will continue to advance in the future, having the effect of reducing the production cost of desalinated water in the future.

Considering what progress has taken place over the past decade in terms of the trend towards decreasing costs of desalinating sea water, one may expect a further reduction in the cost of desalination to a reasonable level. In countries where oil is readily available, such as KSA, the production cost for desalinated water production is less than $0.5 per 1000 gallons. Water generation is combined with future water production in large scale plants of 100 million gallons/day, the cost will probably drop below $0.4 per 100 gallons.

In all attempts to provide large quantities of desalinated water at relatively low cost, the most favoured proposals are for construction of plants with production capacities from 100 to 1000 MGD. Such plants would involve individual distiller units of 25 to 27 MGD each. This may reflect a gradual increase in size of plants required to meet municipal and possible industrial potential increases in water demands.

Proposals for the future anticipate a substantial decrease in the unit cost of desalination of water, due to the consequent savings in capital cost resulting from economics of large-scale plants, shared cost of desalinating water resulting from the generation of electricity or their multi-purpose operations.

Desalination is used by all sectors except agriculture, and it is unlikely that the situation will change much in the foreseeable future. For desalinated water is too expensive under most conditions for irrigation of crops. However, for supplementary irrigation of high-value crops particularly if desalinated water can be mixed with brackish or poor quality water from other conventional sources which can not be used alone due to their high saline content.

The outlook for the use of desalination in such areas is highly dependent on the technology which will be supplied to increase or maintain the stock of conventional water supplies.

The objectives for future years were estimated on the premise that the average annual growth rates for the twelve years will, generally speaking, approximate the seven years for which actual information is available. Thus, it is assumed that the municipal use will continue growing at the historical average annual rate of growth of 23% and industrial use at about 19% with an average composite annual growth rate equivalent to about 23-26%. It is to be noted that total capacity of desalinated water for municipal use is generally less than that for industrial use. However, the rate of growth of the former is almost always higher than the latter. This could be warranted to adjust for urbanisation and growth of cities where the growing urban population may be expected to need more water for municipal and household uses, and adjustment for industry requirements of large quantities of water coupled with relatively lower growth rate of the sector.

The economic development of Saudi Arabia depends to a large extent on the availability of adequate water supplies. Sustained economic growth is impossible as different areas in Saudi Arabia have an acute water shortage, are threatened with possible exhaustion of water reserves or are faced with a steady increase in the salinity of the water.

Conclusions

The Need for Co-ordination

Water control and water treatment are urgently needed to relieve the present situation. In addition, water projects always need to be examined against the master plan for the country. In doing so, fair utilisation, as well as proper planning, can be achieved.

Availability

Availability of adequate water is one of the most important constraints facing farming in Saudi Arabia. The four sources of water are rainfall, groundwater, desalinated and sewage water.

New Sources

The government worked diligently to make drinking water available to all the population. It gave a position to the distribution of water to the various regions of the Kingdom. Saudi Arabia occupies a prominent position in water desalination. It is the largest producer of fresh water from saline water in the world. It has over thirty desalination stations on the shores of the Arabian Gulf and the Red Sea. SWCC activities has recently extended to supply sea water to distant places. The water distribution network had increased between 2,200km to 20,000km from desalination plants to distant places.

To ensure an adequate supply from these sources for the different consumption uses, extensive hydrological surveys and studies to discover new sources of groundwater have been undertaken and a great number of concrete and earthfill dams constructed. Moreover, 26 seawater desalination projects, producing nearly 503 mcm/day have been completed. Due to the increasing municipal water demand by cities on desalination, pipelines are delivering capacities of 503 mcm/d. Desalination plants provide about 50% of the domestic water use of Saudi Arabia. In addition, more than 100 mcm of sewage water after chemical reclamation is now available for farming purposes.

Treated sewage water is one of the sources that has an important role, in meeting substantial portion of agricultural, industrial and recreational sectors. If this water is not available in such a way, they shall be obliged to draw water from the groundwater appropriated for domestic purposes. The MAW carried out several projects to convey treated sewage water to several areas for agricultural purposes, and for industrial purposes. The success in this field and good results achieved encouraged the reapplication of same in other towns.

Inefficient Use

Saudi farmers and urban dwellers are still using water excessively and inefficiently. Traditional methods of irrigation, such as flooding, are still widely used by farmers, causing a waste of this valuable resource and increasing the salinity of soils and water. Efficient water systems such as pivot sprinklers and drip irrigation methods are used but only by few producers.

The Need for Co-ordination

The water problem in Saudi Arabia has been accompanied by inadequate management and conservation measures. Rules and regulations concerning the use of water are not strictly applied. In urban areas, a progressive system of tariffs has been introduced to restrict the overuse of water, but this policy has not been effective because of the low levels of charges which are heavily subsidised. The public awareness of the importance of water and its conservation, as a valuable source of life, still leaves a lot to be desired.

Water control and water treatment are urgently needed to relieve the present situation. In addition, water projects always need to be examined against the master plan for the country. In doing so, fair utilisation, as well as proper planning, can be achieved.

Tihama Asir

The development of water resources of Tihama Asir integrated with the land use for irrigated agriculture is the ultimate objective of the socio-economic planning of the area. This requires an assurance of a continuous flow of dependable data related to the different components of development.

The present rate of groundwater withdrawal exceeds the rate of recharge. There is a gradual decline in the groundwater levels.

The quality of groundwater is deteriorating in the lower part of Tihama Asir. Wells are poorly constructed and no there are controls on groundwater utilisation.

It should be strongly stressed that the work of the development of water resources of Tihama Asir should be carried out jointly and with close co-operation and co-ordination between the people and the Department of Water Development of MAW.

The Future

Due to Saudi's rapid expansion and because the current major water resources, the distilled seawater, and other resources will satisfy water needs only until 2020, controlling the growth of the city seems to be the most effective solution to Saudi's water supply problems.

Recommendations

Because of the tendency of Saudi people to use excessive amounts of water, several measures that could contribute to reduce excessive use should be undertaken. Public awareness campaigns to bring to the attention of everyone the importance of water and the necessary to conservation of this valuable resource should be carefully designed and implemented. Efforts should continue to provide an adequate supply of water for different uses. Increasing attention should be directed to utilise more sewage water after chemical treatment for agricultural uses near large urban areas.

Due to the incompleteness of sewerage and waste water treatment plants in the urban areas, renovated water is used in major cities in Saudi Arabia to irrigate public gardens and to supply some industries with cooling water, and also for agriculture. The pipeline network delivers water for treatment all over the country, approximately 100 mcm. Water reuse activity, however, is expected to increase to 500 and 1,000 mcm in the years 2000 and 2010 respectively.

Distilled seawater is, at present, the major new resource for KSA's water supply. The projects creating seawater desalination plants were initiated in consideration of the growing water requirements and the limited groundwater resources of KSA. The projects were expected to be the most effective solution to KSA's water supply problems. The great distance between the plant locations on the eastern and western coasts to the interior of KSA (460km), and the altitude difference between interior KSA and sea level, makes it the most problematic source as well.

The utilisation of treated sewage effluent is urgently needed to achieve two important goals: it is beneficial for uses such as irrigation and industry, which ultimately lessens pressure on natural resources, and groundwater is prevented from being contaminated by untreated cities sewage water. By completing the proposed sewage treatment plants and the cities sewage network, in cities such as Riyadh, 70% of the water supply will be reused.

Finally, it is hoped that this study will shed light on the water resources, not only in Tihama Asir, the study area, but also in the rest of Saudi Arabia.

Chapter Six

Water Demand and Use

Introduction

A major problem faced by city managers and planners is estimating demand for any given municipal service. MWA and Municipal Water are two utilities supplying basic products to urban areas. The supply of piped water to every city and household requires huge financial investment.

With rapid urbanisation in Saudi Arabia, the demand and delicate situation in its efforts to improve and extend public services, including water supply, to a rapid industrialisation. Tow growth is already dramatically affecting water resources.

This water study looks at the demand and use of water: present water use for agriculture (irrigation, livestock, irrigation methods and development in Saudi Arabia and Tihama Asir), demand and domestic water (in studies of some cities in Saudi Arabia), the supply plans in large towns and villages in Saudi Arabia, domestic and demand for water in Tihama Asir.

Of the vast area of Saudi Arabia, only 0.13% is cultivated and the total area used for agriculture and forests is less than 3%. Of the estimated arable land, only 12% is cultivable.

There are vast land holdings in the Kingdom, 95% of the cultivated land is owned by those who use mechanisation of agriculture and the use of modern techniques in irrigation.

Several climatic and physical factors have combined to make agricultural development in Saudi Arabia a challenging task. Scarcity of water, shortage of skilled and unskilled labour, sand encroachment, harsh climatic conditions and the comparative small size of the average holdings, have all imposed severe constraints on the development of agriculture in the country. In many cases of water exploration, water reaches the surface under its own pressure at a high temperature. The depth of groundwater varies from a few metres to one thousand metres. As part of its plan for the conservation of water in areas which depend mostly on rain water, the Ministry of Agriculture and Water has pursued its programme for the construction of dams, for the control and recharge of water used.

The population growth rate is about 2% a year, which doubles the country's demand for water approximately every thirty years, excluding other needs. Demand will also be raised by the rise in the standard of living, leading to greater household consumption of water. This is due to such factors as the movement of nomadic and semi-nomadic people from primitive to more modern housing, with their accompanying increased water consumption. That is, the economic development of the area, and an increase the population, has led to greater needs for water for domestic, industrial and irrigation purposes. Heavy increases in population, especially in religious cities, and heavy a increase in demand for water by agriculture, means that the basic requirement for estimation of demand for water will be increasing: a total water requirement of some 350 mcm/annum (average growth rate 11% per annum). The rates of growth indicated above are substantial, especially the high population level. In view of the absence of the natural fresh water aquifers near the cities and one of the proposed regional sub-centres, the only available means of providing potable water in the quantities required will be by ground water and surface water.

In any discussion of the uses of water, it must be remembered that some uses result in actual loss of water to the atmosphere as water vapour. Irrigation involves a great loss of water in this way.

The present attitudes towards the urban and rural demands for water would appear to combine short-run economic assessment with private enterprise motives in water resource development. Quantification of these supplies presents a problem because a substantial proportion of the population, particularly in the rural areas, is not being served by municipal water supply systems, but by privately run water trucks or occasional water production and distribution facilities. The latter situation is also not uncommon for the larger or semi-private development projects.

The present situation is serious. Water is being used in the main cities at a rate which exceeds the natural rate of replenishment. This situation is made more serious by administrative overlap and duplication and by private interests inappropriate to so basic a public service as water supply.

Using the same data for the various demand categories as for the other areas, the estimate of 1995 essential specific consumption is 18144 m^3, an increase of 3.8 times since 1975, that is 7% per annum. This rate in the central area is higher than for any other area in the country. This is because of the large proportion of flat accommodation and the small proportion of shanties projected for the year 1995.

Table 6.1 gives only the net domestic consumption figures. To them should be added a percentage for distribution system losses which, for large systems, may be in the range 20-25% of the total supply, and the water demands for the cities under each population range. A high estimate of water demand is 290 mcm/year, whereas a low estimate is 132 mcm/year.

An increase in the use of water for garden watering is likely to be a major component of the growth in domestic water demand. A survey was conducted, and using statistical regression regression techniques, an estimate was arrived at for urban water use by various different kinds of houses. Tables 6.1 and 6.2. below show estimates of urban, rural, irrigation and industrial water uses for the country under each population range.

The majority of the residents of Saudi Arabia's cities have long been unable to cultivate private gardens due to the shortage of water within the cities. At present, the average urban specific consumption in the country is more than 200 mcm excluding agricultural demand but including gardening demand. However, in view of the requirements for public open space as the city grows, the public garden watering demand has been assessed on the same basis as for Jeddah, Al-Riyadh and Jizan. This results ion the high population estimate needing some 16 mcm/y and 8 mcm/y (in Tihama Asir, 2 mcm/y and 1 mcm/y), at tables. Industrial water demand needs a normal allowance of 18 mcm/y and 9 mcm/y (in Tihama Asir, 2 mcm/y and 1 mcm/y).

In Tihama Asir, the socio-economic distribution of population project for the area expected for the year 1995 shows that there are four categories of accommodation: villas, flats, low quality housing and shanties as shown in Table 6.2. Tihama Asir has a large rural population because people in this area are usually farmers who need a large family to help them in agricultural and irrigation processes.

Table 6.1: *Total Water Demand in Saudi Arabia*

Demand	**High Estimate mcm**	**Low Estimate mcm**
Essential	200	88
Private Gardens	24	12
Public Gardens	16	8
Industry, others	18	9
Total	258	117

Table 6.2: *Total Water Demand in Tihama Asir*

Demand	High Estimate mcm	Low Estimate mcm
Essential	25	11
Private Gardens	3	2
Public Gardens	2	1
Industry, others	2	1
Total	32	15

The ideal water consumption of Tihama Asir is sought in domestic uses. The dwelling units of about 10% of the Tihama Asir area population were connected to municipal water systems in 1980. By the year 2000, the dwelling units of an estimated 40% of the population will be connected.

6.1 Domestic water uses

One of the major problems which are faced by the city managers and municipal planners is the estimation of demand for a certain municipal service. Municipal water is one of these basic products of utilities to be supplied to urban areas. There are two main approaches to estimate of demand: the requirement approach and the economic approach. The requirement is the most widely used approach to estimate municipal water demand. It is a simplistic method which enables engineers to design water facilities. The basic assumption in this approach is that the rate per unit of consumption is constant 0.30m^3/person/day or 2m^3/household/day (Ministry of Planning (MP) Fourth Development Plan, 1985-1990). The intensity of water use can be measured by area of land, dwelling units or population, and the amount of water required is simply determined by multiplying the number of units by the rate per unit. The rate per unit is an educated guess based on limited aggregate observations or individual judgment and empirical evidence. It is a rough estimate which is used for future projections by assuming that the rate will increase one or two percent per year. Then a projection for a period of 10 or 20 years is made.

The estimation of municipal water demand of Saudi Arabia is basically a requirement approach. It is based on the estimate of one variable, population projection with an educated guess of the rate per person per day. This is an engineering approach. It helps in a rough way to build the facilities to accommodate the projected requirements and investment takes place without giving much attention to the variables which might alter the rate of consumption. There are certain variables such as climate, lifestyle, income and house type, which have great effect on the rate of consumption per unit of demand, high income people use more water than low- income people.

The approach for estimating demand for municipal water is the economic approach. Here, water is considered an economic good that requires production and optimal allocation of resources. This approach entails efficiency and equity. The efficiency in the production of water requires the optimal allocation of resources and cost effective facilities. The other assumption to ensure equity is a fair pricing scheme. The approach considers some water use as a necessity. For this purpose, realistic planning should consider the economic approach to estimate water demand for domestic use.

6.1.1 Water supply for urban and industrial uses

In the past, Saudi Arabia's greatest use of water was for agriculture, with only a small percentage used for domestic demand. The consumption of water is now much greater due to population growth, industrial expansion and increased agricultural development. This has necessitated greater production requirements. Water utilisation in Saudi Arabia was estimated in 1974 to be 2,460 mcm/y; in 1980 it was estimated to be 4,658 mcm/y; in 19990 to 2000 it is estimated to be between 5724 mcm to 6,523 mcm/y (Third Development Plan, 1980-1985). This trend will increase as the country develops.

Water supply for urban and industrial uses is the concern of the following agencies:

(a) Ministry of Agriculture and Water (MAW);

(b) Municipalities Department, Ministry of Municipalities and Rural Affairs (MMRA); and

(c) Saline Water Conversion Corporation (SWCC).

In addition to overall responsibility for water resource development and national water, the MAW has been concerned with urban and industrial water supply. In the big cities, however, such as Riyadh, Mekkah, Jeddah and Dammam, the SWCC produces water from coastal plants for urban and industrial uses where ground and surface water are unable to provide an adequate water supply.

The investigators selected an approach that combined the population growth and the SWCC *per capita* demand rates, each of which is available on a regional basis. The question arose as to how total municipal demands, thus arrived at, could be broken down over metred domestic and industrial use on one hand, and horticultural irrigation on the other. This ratio varies considerably from one region to another, and from a regional analysis it is concluded that the aggregate national division should be 48% domestic/industrial and 25% horticultural use, in the Tihama Asir area the same figures would be about 25% and 75% respectively, as shown in Figure 6.1a. The national water demand and supply in Saudi Arabia, at present, this situation is illustrated in Figure 6.1b which reveals a comparison between water demand and water resources. Rate of increase with development of water use for domestic/industrial and agricultural irrigation fluctuation in Saudi Arabia for a 25 year period are apparent in all of these figures (demand, agricultural, industrial) increase between

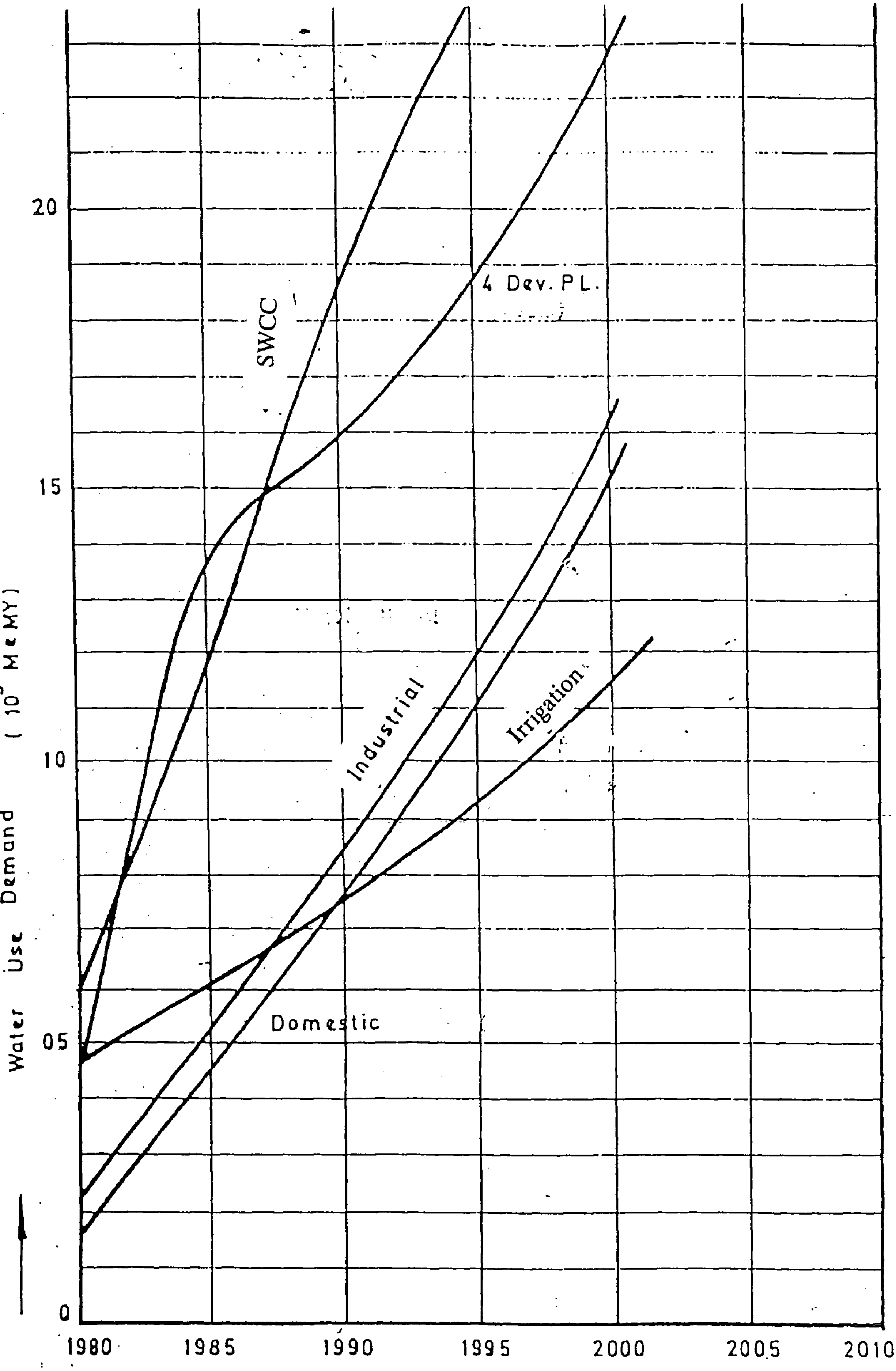
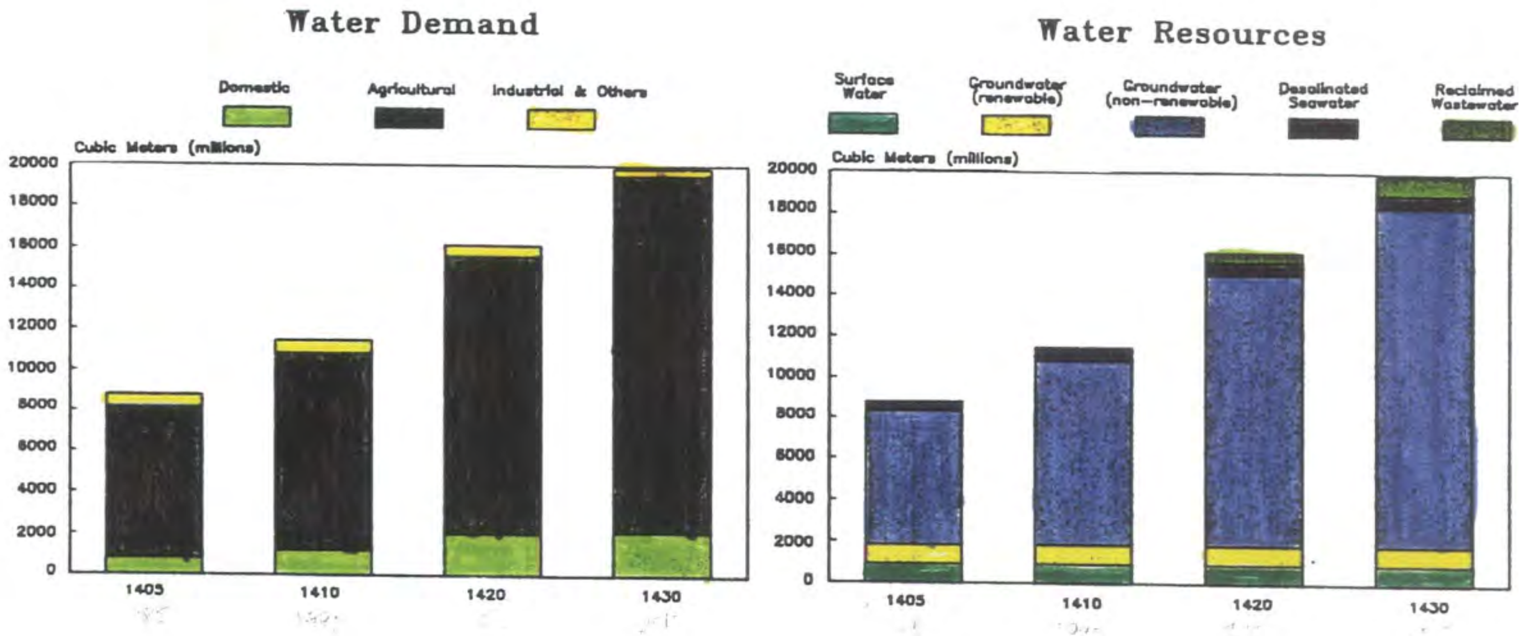


Figure 6.1 a. Domestic / Industrial and Horticultural Water Use Projections

Figure 6.1b:

National Water Demand and Supply



2,000 to 20,000 mcm, and water supply for other uses (surface water, groundwater, desalination, and waste water), which increase along with growing population, from 2,000 to 20,000 mcm. Given the current annual growth rate of Saudi Arabia's use of and need for water, current water resources will last for only 25 years.

Water for irrigation in the KSA is obtained directly from rainfall, natural floods and flood spreading. Pumped ground water is tapped on a small scale only due to the relative abundance of surface water resources (see Chapters 3 & 4; Figures 6.1 a-b).

Numerous ground water investigations have been undertaken, including the initiation of a study of the direct and indirect effects of water transfer from aquifers for oil-well injection. In addition, an extensive programme of hydrological data collection and analysis is ongoing.

The author selected an approach that combined the basic data required for the estimation of demand for water is population and the per capita consumption of water. On the basis of natural increase and migration, the population size is determined. Once the size of population and the per capita consumption are determined then the quantity of water required is determined. The clusters were surveyed and the population of each administrative district was projected for 20 years. The per capita consumption was estimated on the basis of the consumption of houses connected to water distribution network in Saudi Arabia's population is about 10 million, and the requirement of total water 3206.81 x 10^3 m^3/d, and the average person by day is about 326.07 mcm (SWCC, 1990). According to the project, municipal water requirements that more than three million cubic metres of piped water are required daily.

The demand for water has been successfully matched by an increase in water supply and the development of large scale sewerage networks in the country. This has been achieved through extensive public investment in the water infrastructure, so that a high quality piped water supply is available to most of the population throughout Saudi Arabia. On one hand, population growth, living standards and economic development determine the quantity and quality of water demand; on the other, the availability and quality of water influence where this growth will occur and the nature of economic development. In a country with scarce and finite water resources, such as Saudi Arabia, the availability of water is a key element in determining the scale and location of longer-term development. Water planning is, therefore, an integral part of a comprehensive development planning process.

Water supply networks have been completed in a number of towns in which the water department is operated wholly or partially by the Municipalities Department. Completed networks include those in Makkah, Hofuf and Al-Khobar. In these and other towns, however, the provision of adequate amounts of water presents a major problem. Studies for means of increasing water supplies are being carried out in Taif, Makkah and Dammam. A water mixing plant has been completed in Al-Khobar and its connection to the desalination plant has permitted an increase in the supply of water to Dammam and Al-Khobar. The MMRA is responsible for supply in those cities and shares this responsibility with MAW in other cities such as Tabuk, Medina, Abha and Jizan.

The demand for water can be divided into three categories:

(a) Urban demand: This includes domestic, commercial, institutional and general municipal uses. Use by light industries is normally included in this part.

(b) Industrial demand: This refers to use by heavy industries such as chemical complexes where cooling or process water is required.

(c) Agricultural demand: This is almost entirely for irrigation purposes.

6.1.2 Water for industrial purposes

Until recently only a very small percentage of water was used for industrial purposes because of Saudi Arabia's small scale industry. However, because the government now encourages national industries and offers many incentives to promote industry (loans, land and a wide range of facilities which allow for rapid expansion within the country), at the present time there is a general increase in the importance of the industrial sector to the national economy. As a result of industrial development, more stress has been placed on the country's limited water resources. Furthermore, since the country has decided to enter the arena of petrochemical manufacturing, large scale factories were installed and an extensive number of labourers who were not readily available from within Saudi Arabia were needed. Thus, many workers from the nations have migrated to the country, bringing about an even greater demand for water.

The establishment of two new industrial cities has also increased water demand. These cities, Jubail and Yanbu, potable water requirement for these two industrial cities will be met by desalinated water from the existing cities, in the same two cities. The establishment of large numbers of factories creates a greater demand for water within the country. It has been estimated that the increase in water demand between 1991 to 2000 will total between 74.340 mcm/y and 182,310 mcm/y (Noury, 1983). Oil production in Saudi Arabia also consumes large quantities of water estimated at about one billion m^3/y. Most of this water is taken from non- renewable groundwater and some through desalination (Bushnak, 1982).

In general, due to Saudi Arabia's very high oil revenues and the government's plan to decrease economic dependence on the export of crude oil by diversifying economic resources as far as possible, more emphasis has been placed on the fields of agriculture and industry. A wide range of financial incentives, as mentioned earlier, has been offered by the government to the citizens for the purpose of developing these two fields. Therefore, water demand in the country is increasing constantly.

As the process of industrialisation progresses, the demand for water will intensify, even if agricultural requirements could be adequately supplied from brackish sources. To meet both domestic and industrial needs, large-scale desalination plants are used.

6.1.3 Water for agricultural purposes

The acute shortage of water in KSA restricts the amount of land that can be irrigated and the number of livestock which can be raised in any one area. Arable land occupies only about 0.15% of the total KSA land area. At present, only about one third of the total supply of cultivable land is utilised. The most limiting factor is the lack of dependable sources of water.

The shortage of water is considered to be the most severe constraint on Saudi agriculture. This has meant that agricultural activities have been concentrated in oases, around the wadi beds which are abundant in shallow groundwater or springs, or in the highland areas in the south western region of the country where regular rainfall is adequate to meet agricultural needs.

It may be argued that a reasonable supply of water for domestic use, and for ornamental irrigation, is of direct physical and emotional benefit to people, whereas water for irrigated agriculture is not. The agricultural water demands are estimated at 7430 mcm/y. However, recognising the limitations most likely to be imposed on this resource because of high temperatures and transportation costs, salinity and lifting pumps, it is prudent not to boost the estimate. This hydrological reserve may have a life expectancy of about 5 decades at the current rate of withdrawal.

To some extent, demand could be accomplished by substitution, ideally about 66% of all domestic and industrial water supply could be collected, reclaimed and reused, which would add about 800 mcm/y to the supply side. Possibly another 200 mcm/y could be generated by developing even marginal recharge schemes to capture surface runoff, but a gap in the order of 5500 mcm/y would still remain.

The growth in agriculture could not have been achieved without substantial government support to the private sector, ranging across a wide spectrum of activities. Of particular significance were the extent of direct financial support and the parallel wide-scale distribution of land with available water supplies for irrigation. The development strategy for agriculture will temper the pursuit of output growth through further land distribution, with need to conserve critical water resources.

The size of a farm in KSA is usually such that it is served by a single well. A belt-driven pump, powered by a diesel engine, has replaced animals for lifting water. The average pump discharge pipe is 10 cm diameter with a discharge of about 8 litres per second.

The volume of water available for surface irrigation is variable and unpredictable, from a maximum of near 200 mcm in a year to a minimum of 20 mcm. In the past both very small and excessively large floods were equally disastrous to the farmers, the former because of the limited water supply and the latter because of the premature destruction of the aqms frequently resulted in the loss of a major art of the flood down the wadi and out to sea.

The presence of dams built in the area (such as Jizan Dam) now permits a regulated water flow which will prevent the breaching of the aqms. The reservoir behind the dam also permits, in theory, the storage of water for distribution at times of greatest crop need.

With the ma'mal water flows from higher to lower and in theory should be the same from year to year. In practice, however, the path of the incoming flood tends to vary each year. This is partly due to the behaviour of the farmers during the irrigation, who are not above altering the path to their own advantage, and partly because of incomplete control of the incoming flood waters which in consequence sometimes select their own channel.

Tube well irrigation is at present of minor importance in the wadi. However, borehole drilling has rapidly increased over the last 22 years and the present area is swiftly expanding. The tube wells are normally situated outside the areas of regular flood irrigation, notably at the west margin of the area. Although all the tube wells are operated by diesel driven pumps, a few open wells using bucket lifted water still serve small areas of crops.

Land and water management throughout the area is generally of a low standard. No attempts to level the land, even in areas of regular irrigation, were seen. They greatly reduce the efficiency of the flooding system since within any one field the level may vary by up to one or even two metres which results in very uneven and wasteful water application. The flood leaves behind a smooth surface sediment crust up to ten centimetres thick. This is only partly composed of fresh sediment, the bulk consisting of re-deposited surface soil churned up from elsewhere in the fields by the rapid entry of the irrigation water. When this surface layer has sufficiently dried out the fields are reploughed and the crops sown.

The soils of the area are all alluvial, colluvial or aeolian in origin and show little or no signs of pedogenetic development since their original deposition. They are in the main very young soils of an immature nature and the environment is such that little further development can be envisaged with increasing age. The very hot arid conditions prevailing during most of the year combine with the absence or sparse nature of the vegetation to prevent any significant build-up of organic matter in the surface horizons. In consequence, the soil profile is frequently the same colour throughout. The main differentiation in the soils is through the stratification of different textures caused by their depositional origin. Some development of soil structure, into weak coarse and medium prismatic units, has occurred in a number of the profiles but this seems to have reached equilibrium under the present climatic conditions and agricultural practices. Whilst ants and termites were observed on rare occasions in soil pits, they appear to have had little effect on the intermixing of the depositional horizons. The boundaries of different textural layers are normally smooth and well defined. The most profound influence on the alluvium since its deposition has undoubtedly been the effect of cultivation techniques. Indeed, the very extent of the area subject to annual sedimentary deposition has been largely decided by irrigation techniques. Under natural conditions much of the sediment load would have passed out to sea leaving the wadi soils very different to what they are today.

The irrigable surface area depends on the one hand on the water resources, and on the other hand on the topographic situation of the irrigation area: slope, dimensions, distance from the water point. About 80% of the land cultivated by secondary farmers is irrigated. The remaining 20%, mainly in the southern Asir mountains and Tihama Asir, is rainfed. About 70% of the irrigated area receives its water from pits and wells from which water is lifted by pump. Around 10% of the irrigated area gets its supply from springs, and approximately 20% is supplied by occasional flood water which is directed by means of earth and diversion dams, as shown in Table 6.3.1-2. The observation referred to above regarding water use in KSA and Tihama Asir indicated that current water for ornamental irrigation is that allocated for residential land and irrigation. The development by flood spreading is ruled out *a priori* in the case of any surface smaller than 100 hectares. It is estimated that some 80 mcm could be exploited in the future. Irrigation is and will continue to be the largest consumer of groundwater in the country, about 525, 000 ha are presently under cultivation, of the total cultivated area, approximately 120,000 ha are irrigated (Development of Pans - 1975 to 1985).

Recent studies reveal that, due to the government's role of promoting agricultural growth, irrigated agricultural land is increasing rapidly in Saudi Arabia and will continue to increase in the future. Therefore, irrigated agriculture demands more water at the present time and will continue to do so as agricultural expansion continues. Because of the hot summer temperatures in the country, an extremely large amount of water is needed for crops, between 8,000 and 9,000m^3/h are required to irrigate cereals such as wheat and barley, while date and alfalfa irrigation requires about 30,000m^3/h (Noury, 1983; MAW).

The complications arise from the fact that frequently the data are not strictly comparable, either between localities, or between various times. This is due to differences in measuring or monitoring practices, to the adoption of various standards and definitions of residential use, and to different allocations of public uses, such as landscape irrigation.

For the purpose of assessing the scope for residential water conservation, the uses may be classified according to several criteria shown in Tables 6.3.1 and 6.3.2.. The target demand category can serve as a basis for quantifying conservation potential, the figures for purposes are rounded off values of those used by irrigation from different supplies, whilst the garden watering and landscape irrigation rates are estimates of a prudent local greening effort. The latter involves the acquisition of landscape infrastructure, such as plants and irrigation equipment, and the continuing use of purchasing irrigation water.

Table 6.3.1: *Percentage land and irrigation use in Saudi Arabia*

Category	Percentage
Land used by farmers	88
Irrigation by rainfall	70
Irrigation by wells/springs	90
Irrigation by waste water	20
Irrigation by flood water	40

Table 6.3.2: *Percentage land and irrigation use in Tihama Asir*

Category	Percentage
Land used by farmers	80
Irrigation by rainfall	40
Irrigation by wells	70
Irrigation by springs	10
Irrigation by flood water	20

Over the whole country, water is extremely scarce and of very variable quality. It has been established that there are deep aquifers underlying most of the country, and are responsible for the springs which occur in Hasa Oasis, scenes of cultivation since prehistoric times.

The most serious current obstacles to agricultural development is the indiscriminate drilling of wells which has caused the lowering of the water table in many localities. Water pumps have been distributed to farmers on a basis of easy instalment payments, and numerous drilled wells have been sunk (see Chapter 4).

Although water in some aquifers is irreplaceable, it has been decided that since such tremendous quantities are available, its increased use is permissible. Numerous further wells have been drilled in the Salbukh area to meet the increasing water demands by Riyadh City.

Moreover, the traditional, but inefficient surface of gravity irrigation method is still being practised by the farmers throughout most of the country. This wasteful method uses more water than the crop actually needs and increases soil salinity, causing a decrease in agricultural land productivity. Many recent developmental projects have been undertaken by the government to improve irrigation and to increase irrigated land such as in Al-Hasa, Haradh, Al-Kharj and Jizan.

Further development of irrigated areas in Al-Hasa, Haradh and Al-Kharj are also to take place. However, care will need to be exercised in order to eliminate wasteful practices. The principal development of irrigated lands for agricultural purposes will be in the southwest, in Tihama Asir, where Wadi Jizan Dam is intended to hold enough rain water from the mountains to enable irrigation of 6,000 hectares. The great demand which irrigation places on the available water supplies is intensified by the demand for quality and quantity from the cities.

In the Tihama Asir area, the Third Plan (1980-1985) refers to the most extensive water resources, both surface water and ground water. This resource, which is scarcely used to date, forms an excellent development potential for the area. Where the mobilisation of surface water requires huge investment for dam, channels, etc., ground water can be used by means of cheap equipment (boreholes). Therefore it would be profitable to begin immediately the development of the area by the use of ground water. This would allow:

1. the rapid cultivation of some areas where surface water development projects will not be achieved for a long time.
2. the training of farmers in modern cultivation techniques.

The mobilisation of surface water will modify the underflow as the aquifer replenishment conditions will change. Two cases will be examined:

a. the use of groundwater in present conditions.

b. use of groundwater after completion of all the surface water projects.

This is not all available since pumping will lower the water table and consequently the freshwater/saltwater interface will rise. Therefore, pumping should be restricted and confined to the area where the interface rise would not cause contamination by salt water. The areas in which pumping is feasible are those where the fresh water bearing formations overlie the Tertiary impermeable series. By respecting these precautions the extraction in the area could reach 1.5 m^3/s and the only effect would be the ingress of salt water in the lower area which in any case could not be cultivated. It should be noted that this increase of salt water inland would not lead to an increase of salinity in the water of the wells dug in the wadi beds near the sea. These wells supply water to some villages such as Al-Madayah and tap fresh water provided by local infiltration of wadi flood water, the regime of which could remain unchanged.

The replenishment flow may be evaluated by examining the projects which are similar to that for Wadi Hali development. The forecast overall irrigation flow will be 440.10 m^3/year. If it is accepted as for Wadi Hali that modern cultivation techniques can limit recharge to 15% then the infiltration would be between 2 and 2.5 m^3/month, which is similar to the present underflow.

However, the dams will allow an overflow of approximately 150.10 m^3/year, which is the difference between the overall contribution of the wadis and the diverted flow. Various overflow devices are used and these can be classified into two distinct kinds: overflows which permit water to flow over the dam, and overflows which permit water to pass around the edge of the dam, either in a tunnel driven through the abutment or through an open channel constructed on the natural ground. Part of this water could return to the water table as at present. If it is considered that the proportion of flood water which seeps is similar to the present proportion, 0.5 m^3/s would seep into the wadis. The second part relates to drinking water which is important to the population in cities. This involves desalination plants and water towers. There is also the question of digging wells and building dams. Running water is liable to contamination if not held in reservoirs within an area where distribution and exploitation of water can be adequately carried out.

Since the main area of inefficiency comes when the individual farmer applies irrigation water to his field, it seems obvious that improvements can only come with the co-operation of the farmers. These people, however, are not especially well educated and will have to be persuaded that the best crop will only be achieved when irrigation is on a frequent scheduling and when only enough water is added to raise the soil moisture state to its field capacity level.

In more developed societies (e.g. Israel and the US), irrigation users make use of numerical and graphical data such as 'available moisture depletion curves' for their particular soil. Such data is derived from 'water content suction curves' obtained as a soil dries out and the differences are that the 'field capacity level' is taken as the zero moisture depletion level, that the soil moisture content is that which occurs at a suction of 100 cm of waterhead, and that the 'wilting point' is seen as 100% moisture depletion and equal to 2000 cm of suction, in Al-Hassa, Jizan, and Al-Qatif.

The utilisation of water for agricultural purposes varies according to whether the source is:

1. Surface Water
2. Subsurface Water

1. **Surface water**, mainly in the form of brief irregular flows when heavy rain occurs, is diverted from the wadis by suitable dams to embanked areas lying

adjacent to the water course. The water thus collected percolates slowly through the soil into the aquifers (see Chapter Two).

Irrigation using surface water is generally precarious, being entirely dependent on irregular falls of rain. Moreover, serious damage may occur when heavy and sudden floods arise, sometimes destroying the bank and eroding the agricultural lands. Although with surface water irrigation the progressive accumulation of salts in the soil is less likely to occur.

Runoff from the bottom of a field always results, and this may be controlled to avoid erosion and flooding of neighbouring land. Thus there is an interaction between amount of water applied and length of time, and soil water infiltration properties, land slope, and depth of root zone.

Thus, surface irrigation, which is sometimes considered to be wasted water, may be reused many times. In reality, the only water that is truly lost is that which goes to evapotranspiration.

Water conservation thus becomes a major concern on most farms in Saudi Arabia. Traditional farmers were encouraged to line their canals. These lined ditches reduce the amount of water loss and allow more area to be farmed with the same amount of water and fewer irrigators.

The abundance of ground water and surface water is hardly used. Therefore, agricultural production could be considerably increased in Tihama Asir.

2. **Subsurface water** is extracted from wadi alluvium, generally by means of open wells, or rubble or concrete lined wells.

The utilisation of ground water makes controlled and continuous irrigation possible. This is the only type of utilisation in the lower wadis which ensures the growing of fruit trees and vegetables.

Traditional small-scale irrigation still makes up the bulk of the land under cultivation in the country. It is characterised as an area with 4 to 7 hectares under cultivation, but with 25 to 30% of the arable area left fallow each year.

This size farm is usually serviced by a single well, frequently employing a belt-driven powered pump. The average pump discharge pipe is 10 centimetres in diameter, with a discharge of about 18 m^3/sec.

In a number of cultivated areas along the wadis, instances are encountered where surface water is used together with ground water from wells. However, the water crosses the land surface basin, with an entrance from open channels to all fields. The basin is generally long and narrow with the shorter side located alongside the farm channel. The irrigation by flood uses border irrigation. The system is like basin irrigation. The land is divided into strips by small earth mounds. It slopes uniformly away from the farm channel in the direction of water flow. It can be adapted to suit many fields and raw crops, soil and farming practices.

6.1.4 The irrigation system

Groundwater is often the most practical, most rapidly developed supply for irrigation. Storage and water losses are negligible unless artificial recharge of aquifers is practised. Groundwater is usually available during rainless periods and sometimes in more or less rainless dry lands. The agricultural water holds the key to increased production through irrigation.

Irrigation methods, except in a few recently developed areas, are rudimentary. Numerous remains of ancient dams, terraces, irrigation networks and wells, however, are evidence of the existence of a more highly developed agricultural economy in early times. With rare exceptions they have been either neglected or maintained on a very casual basis, a situation which has contributed to Saudi Arabia's relatively low agricultural productivity and to the fact that the area under cultivation remains smaller than the environment actually necessitates.

Perennially irrigated land is usually cultivated every year and in the case of truck farming areas two crops are generally grown annually. The intensity of irrigation is very high; crops are irrigated on average every two days in summer and at intervals of four to five days in winter.

The largest irrigation projects are found at the oases of Al-Hasa, Al-Qatif and at the government experimental farm at Al-Kharj, where large quantities of water from artesian wells are available. Irrigation methods here are the most up-to-date in the country.

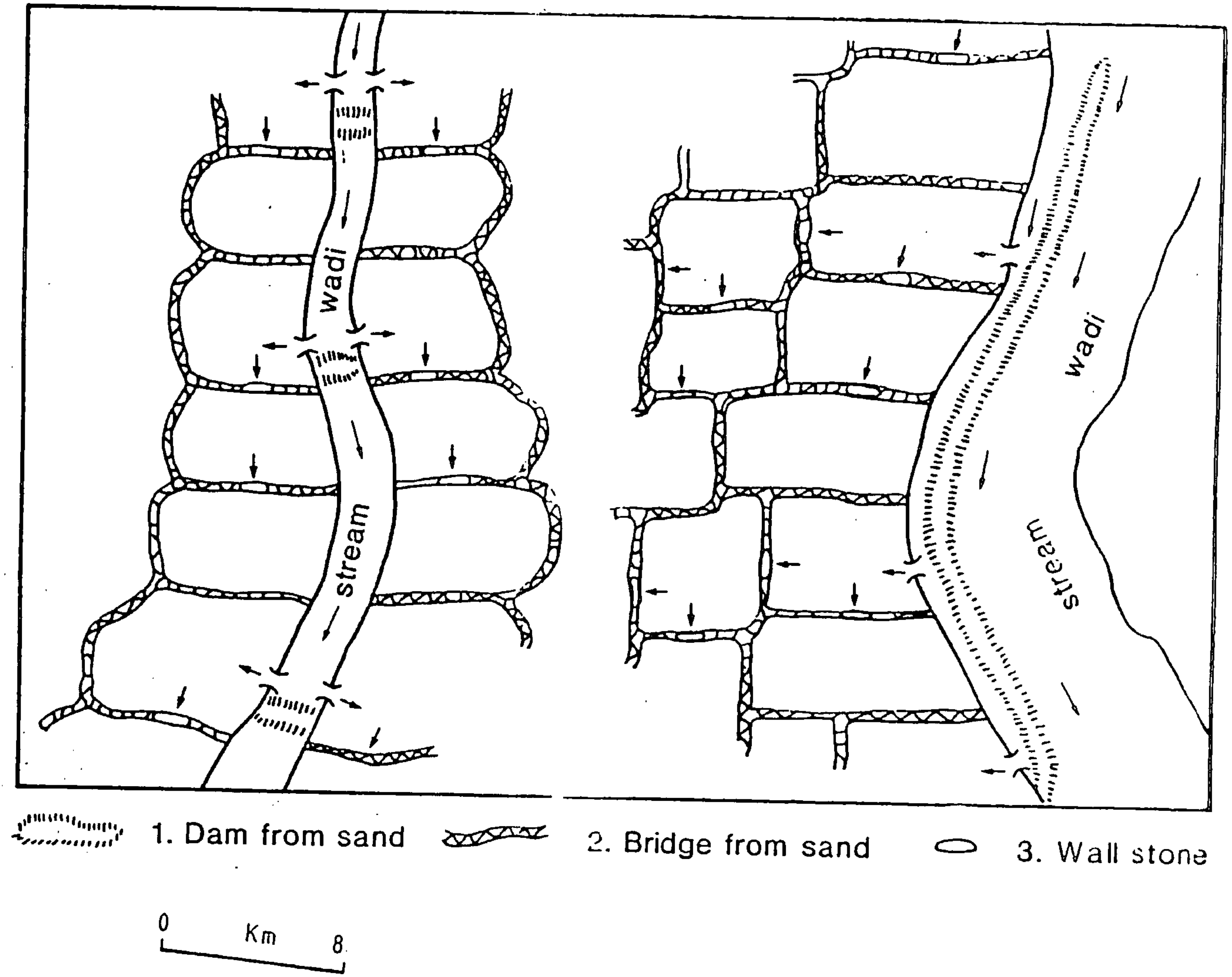
Proper drainage is practised in only few areas. Serious problems of water-logging caused by rising water-table level are encountered in many of the oases, e.g Najed, Al-Hijaz and Al-Hasa. The common practice of excessive irrigation has caused some areas to become malaria infested, especially when the water from springs flows freely 24 hours per day, but only part of it is used during the day for irrigation, thus most of the water gets wasted in sabkhas and depressions, and due to lack of drainage water-logging ensues.

If more than one method of irrigation proves suitable for the terrain, soil and crop chosen, selection is made with reference to the relative merits of yield, water use efficiency, ease of adaptation and maintenance and risks of environmental and socio-economic hazards.

Groundwater is the main source for irrigation in KSA. Shallow man-made wells are still in use in the south western areas where groundwater formation occurs at only shallow depths and where land parcels are small. Figure 6.2 shows water flowing through canals rather than unlined ditches, thus making the field use of water visible above ground.

Figure 6.2

Irrigation Systems in Tihama Wadis



Deep wells, however, are drilled in other areas overlying the underground sedimentary water formations. The introduction of advanced drilling equipment enabled agricultural expansion to new areas, particularly Wadi Dadwasir and the northern part of Qassim, where good water is found at depths ranging from 600 to 1,200 metres. Sprinkler irrigation, specifically centre pivots, was first introduced in 1977 at Haradh. The centre pivot system has more recently been taken up on a large scale by many farms. According to the three main sprinkler dealers in the country, more than 2,700 centre pivots units were sold in 1982. It was expected that over 4,000 additional units were installed in 1983. Most of these systems are used for crop production, mainly due to the government's wheat subsidy policy. Drip, or trickle, irrigation is used for irrigating orchards and vegetables, especially in greenhouses, along streets and in field yards, as shown in Figures 6.3 a and b. The system is used in limited areas such as streets and in the gardens of houses, not in large fields or on farms, and it is claimed to have advantages where soils are salty or the irrigation water is saline. Some gardening is needed. The equipment is easy to manage and there is little on the ground to hinder cultivation. Row and field crops can be grown and there is little standing water (unless water is badly managed).

Wadi floods and surface run-off are significant sources of irrigation water in KSA. Already completed 36 wadis are located in the Tihama Plain, and the flood water exceeds 60% of total flood water in the KSA, which is estimated at 1,265 mcm/year (Figure 6.6).

In order to harness wadi floods and surface runoffs; to reduce flood damage; to increase the recharge of aquifers; and to expand the accessibility of irrigation for agriculture in major flood wadis such as Jizan, Dammad and Najran, the government had, by 1981, built more than 200 dams in various locations in the KSA. In addition, numerous diversion weirs were built to store runoff water and use it for irrigation.

Well water is drawn to meet irrigation system requirements. In Tihama Asir, the distance between the wells varies from 450 to 500 metres. Each well is designated to irrigate approximately 8.0×10^5 m^2. [Source: MAW]

Four systems of irrigation are used: the open canal system, the pipe irrigation system, the sprinkler system, and drip irrigation.

a. The Open Concrete Canal System

This has been regarded as the most economical irrigation method. The scheme, comprising main and lateral canals, is laid out in a simple way which can easily be maintained and supervised. Two main irrigation canals are erected along either side of the developed area. The lateral canals branch off the main canals at a narrow angle parallel to the Wadi centre.

In the open canal system the loss of water by evaporation is great, especially in the very hot dry summer. However, two hours are estimated for irrigation time per hectare. This allows for a frequency of irrigation of 6 to 8 days due to soil and weather conditions. Frequencies of eight days cannot be observed without great losses and damage to crops. Therefore, the change of irrigation frequencies to four days necessitates a decrease in cultivated lands per well, and hence this system cannot reach its planned efficiency, as shown in Figures 6.4, 6.5, 6.6.

b. Low Pressure Pipe System

Perennial irrigation from wells and pits, from which water is lifted by centrifugal pumps, is used in 70% of irrigated areas. Flow of water by gravity into conduits from surface springs accounts for about 10% of the irrigated areas. The torrential floods of the monsoon season, diverted to fields by stone dams in the wadi beds. Tihama earthen dams are used for catching flood water. These dams, however, are often swept away such as in Wadi Baysh.

Figure 6.3a:

Irrigation by Gun Spraying System used for Gardening in Jeddah

Figure 6.3b:
Drip Irrigation System used for irrigating street in Taif in KSA

Figure 6.4

Basin Irrigation System uses Bar bewteen each field in Jizan

***Figure* 6.5.**

Basin Irrigation System at Wadi Bysh in Tihama Asir

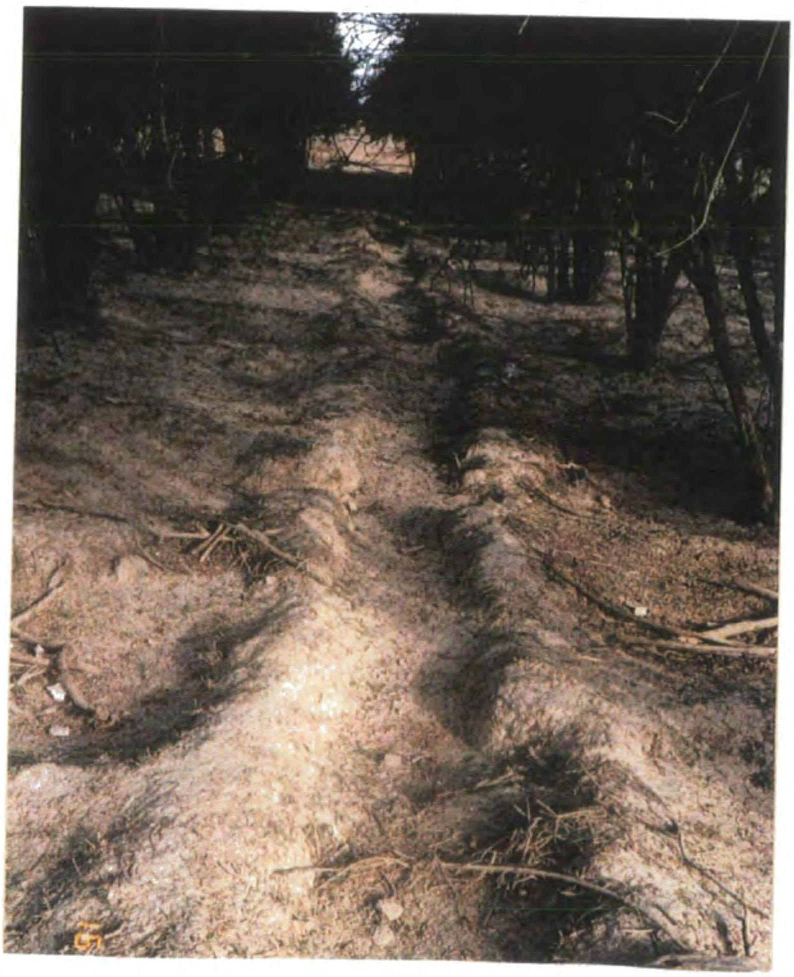


Figure 6.6:

Al-Duriyah Dam and Irrigation System

This is employed on a small scale and two well areas only are under this method of irrigation. The pattern is laid out similarly to the open canal system. This system enables more favourable field operations such as changing the partition of the field, soil management and the machinery application. Also, in terms of water conservation, this system is more efficient than the open canal system. Since water is a precious asset in KSA the favourable conditions for applying this system may offset its high construction cost.

c. Sprinkler System and Centre Pivot Unit

Sprinkler system with a centre pivot unit are being used on a large experimental scale. The water is pumped from the wells in separate compensating basins each of 250 m^3 in order to provide a reserve during the shifting of the movable pipes. Two sprinkling pumps output pressurised water into the buried main pipeline. The hydrants are joined by portable lines to which they deliver the water, as shown in Figure 6.7.

The sprinkler pattern is said to allow for an equal distribution of the water even when it is windy. In applying this system, the high evaporation losses due to the dry climate may be offset by evaporative cooling effects on the crop.

Sprinkler irrigation, if designed and operated properly is a very effective water application method. One which can be used over a wide range of soil conditions (the method is especially useful where the soil is coarse textured, sandy and/or has low moisture retention capacity) and on flat terrain where surface irrigation would be impossible. The control of water is easily automated to allow a close match of crop water needs to flow rates. Moisture losses can be quite high as droplets of water evaporate before reaching the ground. For these reasons, water is best sprinkled in still weather conditions, at night or on dull days. Even so, water losses are still probably less than would occur using surface irrigation (Stern, 1979:17). Where conditions are

Figure 6.7: *Private sprinkler irrigation*

windy, sprinkler irrigation may be seriously hindered. Attempts to apply water when the air is not still enough generally leads to uneven application.

Where water supplies contain salt, sprinkler irrigation may remain unsuitable because of the droplets deposited on at least some crops causes burning of the leaves and moisture stress (John, 1980:171).

Perhaps the most important aspect of the development of irrigation techniques hitherto have concentrated on centre pivot, of which there are 15,000 operating in Saudi Arabia. The longest of these, to be found mainly in the Qasim area north of Al-Riyadh and Al-Kharj just to the south, are more than half a kilometre long and create the huge circular fields that are a striking sight.

Sprinkler and centre pivot irrigation systems achieve the same level of irrigation efficiency. However, the irrigation efficiency of these systems is actually very good, considering a soil type and climate especially in Al-Hassa oasis and is partially a result of the farmers' awareness of these conditions and their practice of irrigating at night. In south-western KSA, where shallow man-made wells are still in use and ground water formations occur only at shallow depths, and where land parcels are small, with climate and soil type especially when the farmers irrigate at night during the summer.

The major disadvantages of sprinkler irrigation at present are its tendency to suffer from blockage or abrasion of sprinkler heads due to sediments and algae in the water supply; the relatively high cost of equipment; the need for powerful pumps (which mean relatively high energy costs); and the need for skilled staff for installation design and management. It is likely that the cost of sprinkler irrigation hardware will fall, but even if it does not, today's typical installation cost is around $2,000/ha (Stern, 1979) is not favourable when compared with the costs of establishing large-scale surface irrigation schemes in KSA which is commonly around $3,000/ha. [Source: MAW]

Low and medium pressure sprinkler systems probably offer more potential for developing countries, but there is the problem that with low pressure systems water droplets can be large and cause crop and soil damage.

In Saudi Arabia other irrigation projects are found at Al-Washem, Sudair, Dawadmi, Ammareya, Hafer Al-Butin, Taif, Khamis Mushdit, Wadi Najran and Al-Kharj.

Several large scale irrigation and drainage projects have been initiated. These aim to introduce a more rational and efficient use of water and to overcome the problem of wastage and salinity inherent in many traditional irrigation systems whilst at the same time attempting generally to improve existing rural and agricultural systems.

Furthermore, F.A.O. studies suggest that techniques such as wheel-mounted sprinkler laterals with a pipe driven frontal movement are very economical if properly managed.

Many of the large farms in Saudi Arabia in particular are therefore implementing these systems. Most of these systems are used for crop production, mainly due to the government's agriculture subsidy policy. It costs more that SR 562,000 (about £80,300/$149,870).

d. Drip irrigation

Drip irrigation is the method most recently introduced to Saudi Arabia. In this system, water is delivered to the soil at a very low rate by drippers, so that all of the water is absorbed by the soil near the dripper, as shown in Figure 6.3b. This system is particularly advantageous for widely spaced rows crops, for example, in orchards or vineyards, because water is applied directly to the plant area and not over the entire soil, as is the case with sprinkler systems. Since the water delivery rate is very low and slow, this system can be used on all soils with no runoff.

The drip irrigation methods is used for vegetable growth under greenhouses. It is also used on farms. It can be expected that this method will be adopted more widely in the future and compete with sprinkler methods.

The irrigation areas under cultivation in Saudi Arabia are around the eastern region's oases, and the central and south western regions. However, salt accumulation in most of the cultivated lands has caused a decline in soil productivity. The government recognised the new system of irrigation and drainage. The objectives of the new irrigation and drainage are as follows:

- To reclaim most of the lands which were cultivated before and to increase the cultivated area from 8.0×10^7 m^2 to about 2.0×10^8 m^2 [Source: MAW]
- To replace old irrigation ditches with new cement canals and to install a new drainage system (this in Al-Hassa).
- To achieve optimal irrigation efficiency and high soil productivity.
- To establish extension services in order to change the traditional agricultural methods to modern methods.
- To make use of every drop of water available by developing maintenance plans and other projects.

The new irrigation and drainage project has failed to achieve one of its purposes, the increase of the productive land.

The study has given several reasons to explain why the area of agricultural lands are the same as before the new irrigation. One of these reasons is that the water supply is limited. The other reasons are that the water demand has increased and that both farm and field irrigation efficiency are very low.

Because the water supply is limited, competition between users has increased. Therefore, a greater interest in achieving higher water use efficiency has been projected. It has been suggested that irrigation water use efficiency can be improved by taking the following steps:

a. determining the water requirement for crops and leaching;

b. irrigation during the nighttime hours;

c. covering fields with mulch

d. improving ditches in the fields, and;

e. developing better irrigation methods.

Another response to the need for an increased water supply has been the initiation of several large scale irrigation and drainage projects which aim to introduce a more rational and efficient use of water and to overcome the problems of wastage and salinity inherent in many traditional irrigation systems whilst at the same time attempting to improve existing rural and agricultural systems, and that the best examples in Saudi Arabia are the Al-Hassa Oasis, the Wadi Jizan, the Faisal Settlement and Al-Qatif project.

A. Irrigation Methods of Al-Hassa Oasis

The Al-Hassa Oasis area constitutes the largest single irrigated area in the east of Saudi Arabia. It is 40 km west of the Arabian Gulf, 100 km south of Dhahran and 320 km north east of Al-Riyadh.

One of the most important projects is the irrigation and drainage project of the Al-Hassa area. This project is located in the eastern region. It is famous for its numerous artesian springs, which number more than sixty, because the amount of water from the springs was greater than what was needed for the cultivated areas, the water level was high and caused for formation of swamp. The need for an efficient irrigation and drainage system was therefore necessary so that the springs and wells in this area could be preserved and the standards of cultivation could be increased (MAW).

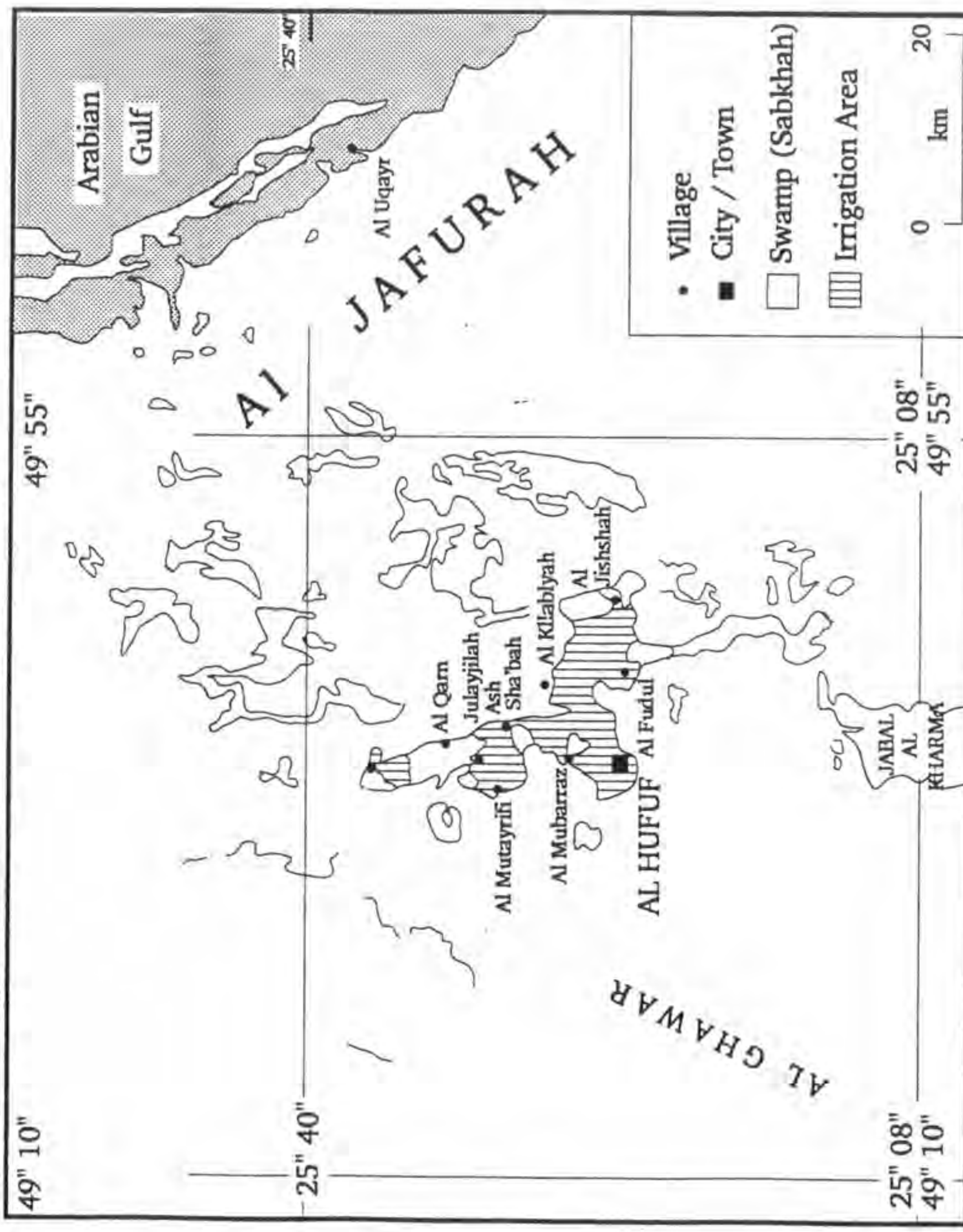
Al-Hassa Oasis can be divided into two parts. The eastern part stretches from the city of Al-Hufuf, located on the south west edge of the oasis, to about 16 km toward the east to the town of Al-Jishah, with an average width of about 9 km, and a population of 60,000. The northern area extends from Al-Mubarraze City in the south to Al-Uyum City on the northern edge of the oasis, with a total length of some 17 km, and between Al-Mutairifi on the west and Al-Shabab on the east with an average width of about 7 km and a population of 28,000, together with the 48 villages in the area giving a total population of around 250,000 (1979) (Figure 6.8).

With over 30,000 acres under cultivation, including some 3 million palm trees enclosing the two towns of Hufuf and Mubarraz in addition to over fifty other settlements, Al-Hassa is the largest oasis in the Arabian Peninsula covering an area of about 180 km^2. It is "L" shaped and extends about 16 km west-east and 20 km north-south. Water from these oasis is drawn mainly from 330 wells and 60 natural and man-made artesian springs.

The Al-Hassa Irrigation and Drainage Authority (HIDA) was set up to be responsible for providing water for irrigation. HIDA also advises farmers on new crops and gives instruction in the use of fertilisers, insecticides, and in new growing methods.

Whilst in general the project has been successful on the production side, a number of problems have developed. A major difficulty surrounds the patterns of land ownership and water useage. Before the government's irrigation scheme, well owners and farmers with water rights paid for the labour by making their water available.

Fig. 6.8. Irrigation Area At Al - Hassa Oasis



Many areas remain uncultivated simply because no one has been able to prove ownership. To make the irrigation scheme's water freer to every farmer, compensation had to be paid to well owners, but again conflicting land ownership claims have held up the expansion of irrigation.

The agricultural productivity in this area was decreasing due to the increase in soil salinity, roughly 600,000 tons of salts were brought to the cultivatable land annually by irrigation water. This was a result of the traditional flood irrigation method practised by farmers, where fields were irrigated and the water was then re-used by means of open canals flowing from field to field.

Since the scope for agricultural development in the Al-Hassa oasis is determined by the availability of irrigation water, optimum use should be made of the water resources. To optimise water use, farmers may need substantial financial support. Construction of drainage provisions and land reclamation are investments which the average farmer cannot make.

Subsidies will therefore have to be given to channel production into the most efficient areas. The Al-Hassa experience indicates that despite the difficult problems which hinder the country's agricultural development, there are in principle a number of ways these problems can be overcome.

For a long time, farmers in this oasis have faced the severe problems of soil salinity and sand dunes. Salinity is the direct result of both the overuse of artesian irrigation water, which is very saline, and the high evaporation due to climatic conditions. The oasis is entirely surrounded by desert, mostly sand-dunes to the east and north. and a flat thin mantle of sand over a limestone floor to west and south. Farmers of Al-Hassa are faced with the gradual invasion of wind blown sand into their fields and gardens. Only a small part of the oasis was cultivated due to the above problems, and agriculture was based primarily on the production of date palms as cash crop, as well as alfalfa which is used as feed for livestock. The government of Saudi Arabia realised these problems which put constraints to the development of agriculture in the oasis.

About 95 per cent of the construction operations for Al-Hassa water irrigation and distribution scheme have been carried out and the project was expected to be completed in 1971. However, no proper drainage system was ever built and consequently and land from one garden to another becomes progressively more saline, before finally ending up in the surrounding sabkha. Moreover, much water was wasted through evaporation and seepage owing to the unlined and uncovered nature of the irrigation channels. In effect, therefore, the water was both saline and inefficiently used. The area under cultivation shrank by around 8.0×10^7 m^2 to around 4.0×10^7 m^2 in the 20-30 years prior to 1967 (Figures 6.9 and 6.10). The first figure is given here to show one of the main canals of the irrigation and drainage network in the centre of the plain garden in Al-Hassa. The second shows the excess water which is drained from the Hassa irrigation project.

In order to overcome these problems, in 1961 the Ministry of Agriculture and Water commissioned a major development design project and between 1967 and 1972 a new water extraction, distribution and drainage scheme was constructed.

The basic aims of the project would appear to be threefold:

1. The reclamation of 2.025×10^8 m^2 through the introduction of improved drainage conditions. [Source: HIDA]
2. The conservation of water resources through the introduction of lined irrigation channels and water saving irrigation techniques.
3. General agricultural and rural improvement.

Figure 6.9: *One of the main canals or irrigation and drainage network in Hasa*

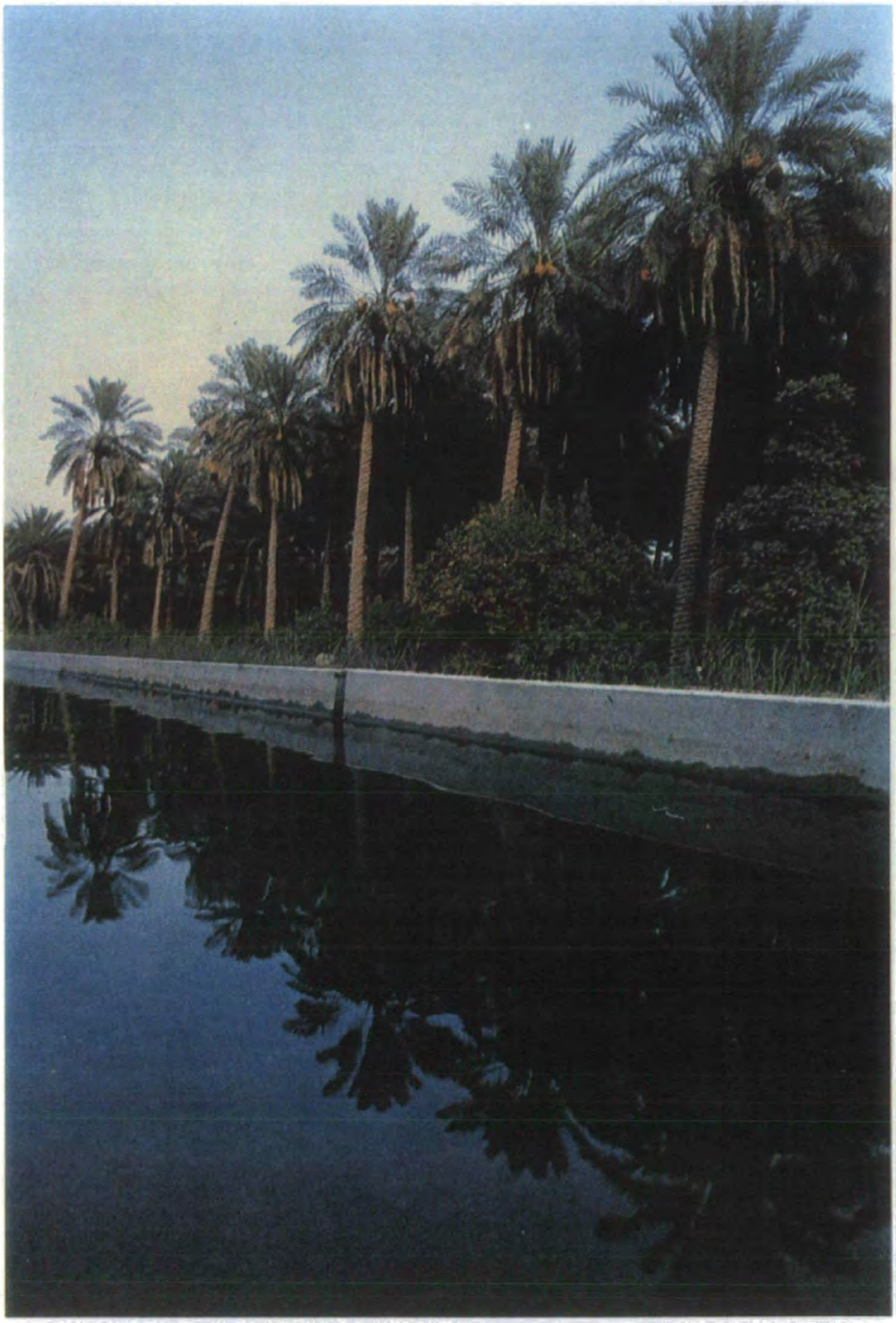


Figure 6.10: *Hasa irrigation project water drained*

The above projections of water use for agriculture are based on a water use of 172.8 m^3 per 10^4 m^2, the average for 1978-1984. A particularly promising technique in that respect might be the use of drip tubes suspended from a central pivot system, thus all but eliminating evaporation losses. However, new farms are now able to produce 2 to 4 times as much per unit area, probably with some reduction in water use as well. Figure 6.11 shows the Haradh and Al-Hassa irrigation projects. At the centre of Haradh is the 40 km long irrigation area in Wadi Sabha. Some of the deep wells are equipped with pumps each with a capacity of 300 m^3/hour, pumping water into two main distribution canals running parallel to the wadi.

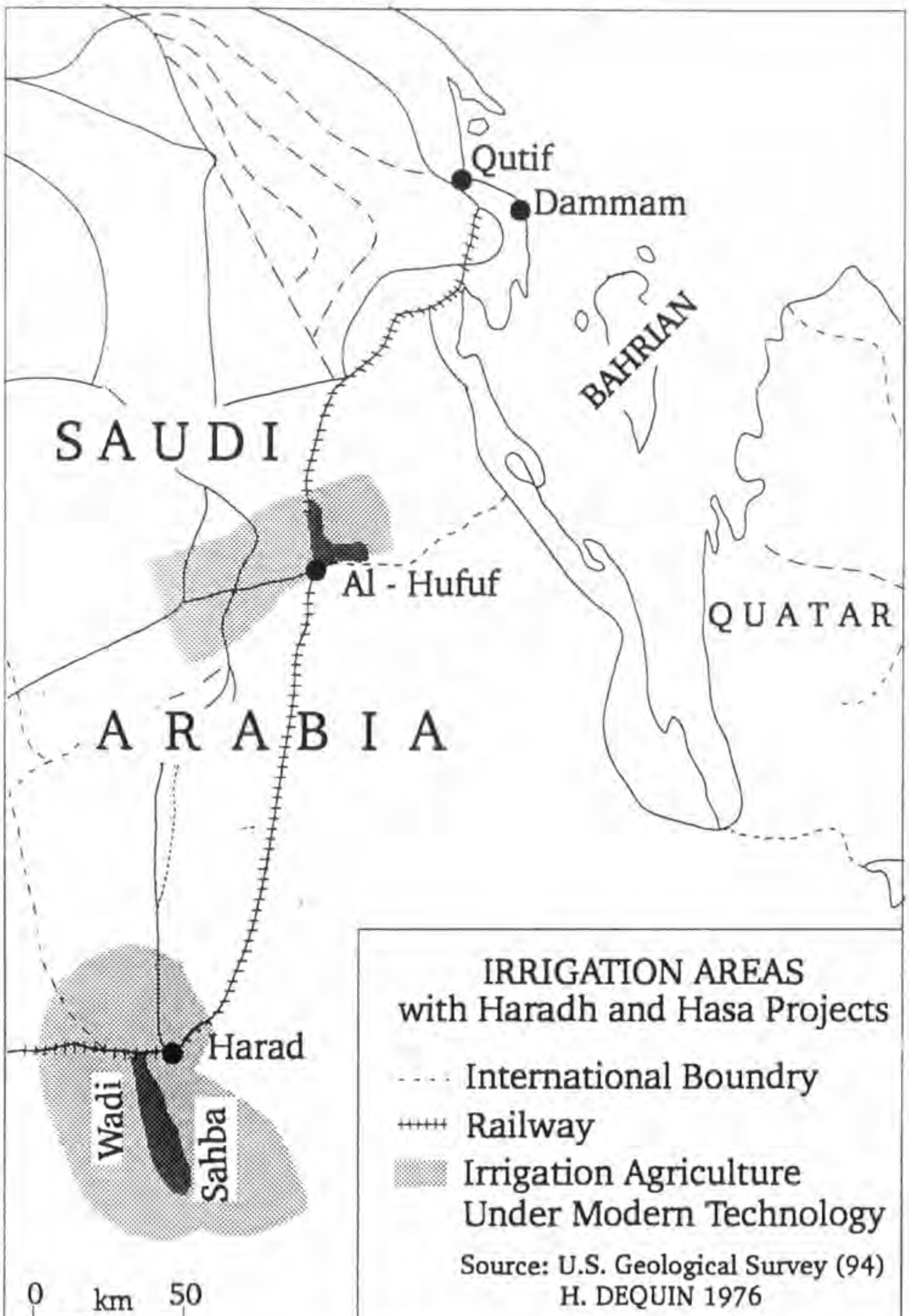
The Al-Hassa irrigation system consists of two canals reaching about 1840 km to provide about 400 mcm/year. These canals provide water supply for Al- Hofuf, Al-Mubarraz cities and 48 villages.

The purpose of the project is to control irrigation and drainage, to reclaim 50,000 acres, to repair springs and wells that have been blocked by sand, to eliminate stagnant water and swamp, to treat the palm trees that were affected by the rotting soil and to introduce new crops.

B. Faisal Settlement of Irrigation Drainage

Haradh is located along the Dammam-Hufuf-Riyadh railway in the Eastern Province, some 150 km west of Hufuf, 303 km south-west of Dammam and 265 km east-south-east of Riyadh. The project area is at an elevation of 130 m above sea level and stretches some 40 km from the railway station of Haradh in a south-eastern direction and is about one kilometre wide, crossed by Wadi Sabha. The area is gently undulating with a chain of hills on both sides of Wadi Sabha and interrupted with side tributaries. The general slope of the area varies from 0.5 to 4 m towards the centre (Figure 6.11).

Fig. 6.11 Irrigation Areas



Its main project has been implemented to develop water resources for agricultural purposes. The project was completed in 1971 and consists of fifty-two wells. It takes its water from the Umm-er- Radhuma aquifer. Each well irrigates about 80 ha. This aquifer was too deep to be accessible by traditional technologies.

The location was chosen for the following reasons:

1. Availability of underground water resources discovered by Aramco during the exploration of oil.
2. Favourable soil and topographical conditions.
3. Good communication.
4. The existence of Bedouins who live in the nearby areas and who have irrigation fields in the Wadi Sabha.
5. Availability of adjacent gas-oil separator plant.

Previous agricultural development established that the area was underlain by the extensive water supplies of the Um-er-Radhuma Aquifer. Therefore the government initiated a programme which involved the drilling of 52 deep wells. The high level of technology which was introduced in the water supply and drainage system was beyond the management of the relevant technical experience, the planned small-farm irrigation agriculture envisaged at Haradh. Rather, if water and soil resources are to be successfully developed then some attempt will have to be made to interest the right people in developing agriculture in the country.

The upper aquifer is in the Um-Er-Radhuma formation at a depth of 150 m to 180 m below ground level. The aquifer outcrops some 50 km west of Harad. The lower aquifer is the Wasia Sandstone Formation lies at a depth of 850 m.

Water is available in large quantities from both aquifers for agricultural development. The watersheds of Wadi Sabha and other tributaries contribute some water to the aquifer along the length of the outcrop.

An irrigation network consisting of main and secondary canals has been constructed to irrigate some 3.0×10^7 m^2. [Source: MAW] The main canals constructed are of concrete parabolic shape of five metres wide, placed on both sides of the valley. The laterals are also concrete parabolic and branched from the main canals at about 60° angle and some 150 m apart. All sections off the canals are placed end to end with joints sealed with specially formulated asphalt base compound and supported by concrete saddles resting on sandy soil.

Due to great variations in temperature and due to lack of water, cracks are occurring and continuous maintenance of the concrete is necessary.

The sprinkler irrigation network was completed and the following crops were grown: 1.8×10^7 m^2 of wheat, 2.0×10^7 m^2 alfalfa, 6.8×10^6 m^2 forage and Rhodes grass, and 6.0×10^6 m^2 sorghum. [Source: MAW] The several production opportunities available are: the raising of sheep, cattle, crops and fodder.

An irrigation network consisting of main and secondary canals has been constructed to irrigate some 3.5×10^7 m^2 water distribution. In 1970 the basic irrigation and drainage system, was installed.

The Faisal Model Settlement scheme is also nearing completion. About 90% of the construction operations for the project have already been executed. A total of 71 km of main irrigation canals, 280 km of secondary canals, 45 km of main drainage canals and 260 km of secondary canals were constructed; 14 bridges were built and the wells each providing 0.75 m^3/s water have been drilled.

C. Al-Qatif Irrigation Development

Al-Qatif oasis is one of the two largest and the most prosperous oases in the Eastern Province. It stretches some 20 km along the lowlands of the Arabian Gulf. The project area covers some 7,200 ha. located on the coastal belt some 7 km northeast of Dammam City.

The topography of the area is fairly flat, ranging from about 9-13 m above sea level and sloping down eastward to the Gulf to about 2 m near the coast. The oasis is one of the most densely populated areas in the Eastern Province with a total population of about 400,000 (MAW).

The main sources of irrigation water are from Altat and Khobar Aquifers of the Dammam Formation and partly the Um-er-Radhuma. The Altat is some 50-70 m thick with its top at 20-90m below the ground water level. It is partly dolomitised limestone at the top, and shale and marl at the bottom.

The Khobar is some 35-50 m thick and at 50-230 m below ground level. It consists of skeleton dolomite limestone and dolomite lying over argillaceous limestone with shale inter-bedded at the bottom.

Both Alat and Khobar are free flowing in the eastern part of Qatif, over which the level of water table in the far east is dropping to about 3 m below ground level. The two aquifers are intensively exploited by means of over 300 hand dug and drilled wells. Many of these wells have already been abandoned (MAW).

The Um-Er-Radhuma Formation with its top at 105-210 m below ground level, is composed of dolomitic limestone, dolomite and highly chalky limestone, marl and sometimes anhydrite inter-bedded in the lower part (Noury, 1983).

The Alat and Khobar are separated from Um-Er-Radhuma by a non-porous layer of clay at the bottom of Neogene Complex. Lack of control of free flowing water has led to a continuous drop in the artesian pressure of the aquifers. Moreover, incorrect ways of drilling wells have resulted in the various aquifers becoming connected with each other and with the surface formation. The Khobar aquifer has dropped 4.5 m in twenty years and is continuing to drop down.

The electrical conductivity of water of various wells in the area is 2000-28000 for Alat and 2000-36000 for Khobar and Um-Er-Radhuma 2050-3500 (MAW). The quality of water is not normally suitable for irrigation, besides the lack of adequate drainage in the project area. Thus, salts have accumulated in parts of the cultivated areas, rendering them unproductive and they have been abandoned.

It was clear that lack of adequate water control was one of the major factors responsible for the decline of agriculture in Qatif area. To reverse this trend, it was regarded as essential that solutions be found to three basic and related problems:

a. Lack of adequate drainage.

b. Uncontrolled water supply and distribution.

c. Inadequate and insufficient water distribution.

Although the construction of the four main drainage units was completed and benefits were already apparent, additional drainage facilities would be required, especially if an overall irrigation plan was to be adopted.

To develop Qatif Oasis the main objectives are:

a. To ensure sufficient and good quality of water to irrigate the whole Qatif area.

b. To avoid drainage water as much as possible from the Um-Er-Radhuma aquifer.

c. To reduce canal water losses and water waste.

d. To reduce soil salinisation by providing proper drainage networks MAW.

The studies included surveys in order to present the potential cultivable land, soil surveys and water surveys in order to determine the optimum rate of water extraction complete designs to irrigate the cultivable area.

Al-Qatif experienced an increase in agricultural activity associated with oil development in the region, leading to a rapid increase in the number of wells and in groundwater extraction. This has led to a drop in artesian pressure (the water table in the Al-Khobar aquifer has dropped by 4.5m in 20 years) and a rise in salinity. Surveys by Aramco point out that this has been exacerbated by incorrect well drilling and the subsequent interconnection of aquifers.

As a result an irrigation plan for the oases was formulated which was aimed at alleviating the lack of adequate drainage, the uncontrolled supply and distribution of water, and the inadequate and inefficient water distribution. In 1970 the basic irrigation and drainage system had been installed.

The cultivated areas have been developed where water has been plentiful, according to whether irrigation is constant (groundwater) or discontinuous and unreliable (floodwaters of the wadis) (See chapters 3, 4).

6.1.4.1 The Development of Irrigation in Tihama Asir

The amount of land under cultivation is rarely equal to the irrigable surface area and very often it represents only quite a small part of the latter. Water requirements vary from 8,000 to 12,000 m^3/ha/year for the land in Tihama Asir and are on average 4,000m^3/ha/year for the land of other areas. The peak flow determines the capacity of the intake structures. Its maximum value has been cited at 50 litre/second/ha., which gives an intake flow of 5 m^3/s/1,000,000 m^2. Although it appears high, this figure of 0.5 $m^3/s/ha$ is reasonable if advantage is to be taken of Wadi floods, which are of extremely short (from 4 to 20 hours) duration.

In order to reduce the level of food imports and increase agricultural production, the government in the 1970s embarked on an ambitious and varied programme of agricultural investment. The Ministry of Agriculture and Water (MAW) works closely with the Saudi Arabia Agricultural Bank (SMB) and other agencies. The government has made food self-sufficiency one of its foremost priorities, and the progress towards this goal that has been made in just a few years is quite impressive.

The rapid expansion of agriculture started when the MAW increased the size of land plots for free distribution, and the SMB had available the large funds necessary for such development.

The subsidy structure in the Tihama Asir is manifested in two ways as it affects water use:

1. Consumers are not charged for the actual cost of producing water.

   The first of these is reflected in the actual production cost of municipal water, even though the individual consumer may not be charged, society is, because funds that could be used elsewhere are diverted to subsidise water production.

2. Agricultural water consumption is encouraged by subsidies of selected agricultural produce.

The second subsidy can also be related to water by placing the total burden of agricultural subsidies on the water input of the agricultural enterprise.

In Tihama Asir the scope for future agricultural development includes both the horizontal and vertical expansion of cultivation. Given the constraints of water, land, climate and labour, it seems that the scope of horizontal expansion in area is limited in the short and medium terms, but that considerable increases in agricultural production can be achieved through vertical expansion.

The present method of flood irrigation applied to agricultural land in the area has been practised since time immemorial. More than 95% of the land has been used for cultivating sorghum, producing both grain and stalk. The construction of the channel and the partial irrigation network has had a very minor effect on changing the cultural practices and on the adoption of new crops, since the method of irrigation stayed the same. Its main effect has been on protection against floods, and on the control of irrigation water releases and distribution according to plan.

A total of about 105 km^2 of fallow land was distributed since the regulations for the distribution of fallow land. A total of about 4,000 square kilometres is pending distribution (some 500 ha are set aside for housing, offices, roads and other facilities). As a result of irrigation water, it is proposed by farmers that irrigation of an area totalling 3.0×10^7 m^2 be used under a spate (flood) irrigation system, and an area totalling 3.0×10^7 m^2 be converted to the surface irrigation system, because evaporation in Tihama Asir is very high (MAW) (see Chapter 2).

a. Irrigation in Wadi Jizan

Due to the great social and economic evolutions over the past decade, the flood irrigation system has not been economically feasible for most of the farmers. They started drilling groundwater wells at increasing rates, to be able to produce greater varieties of crops including vegetables and fruits under perennial irrigation system. This activity has been practically uncontrolled and has resulted in an over-exploitation of groundwater resources and the consequent deterioration of its quality and quantity.

Irrigation water is normally released four times a year depending on the availability of stored water in the reservoir during the four planting seasons; namely, Al-Saudat, Al-Kharif, Al-Shab and Al-Mukhrat.

On average, the water requirements under the present flood irrigation system was found to be about 10,000 m^3/h and the conveyance losses through the wadi course and irrigation canal system amounting to about 33% of the water released from the dam. This gives an average depth of water application to the fields of about 65 cms (MAW). This amount of water is used to grow a single crop, mainly sorghum by a single watering.

Wadi Jizan is one of the most significant wadis of southwest Saudi Arabia. Although the area traditionally had only very limited and primitive agriculture, Wadi Jizan showed favourable possibilities as a pilot area for irrigated agricultural development in this region (see Figure 6.12).

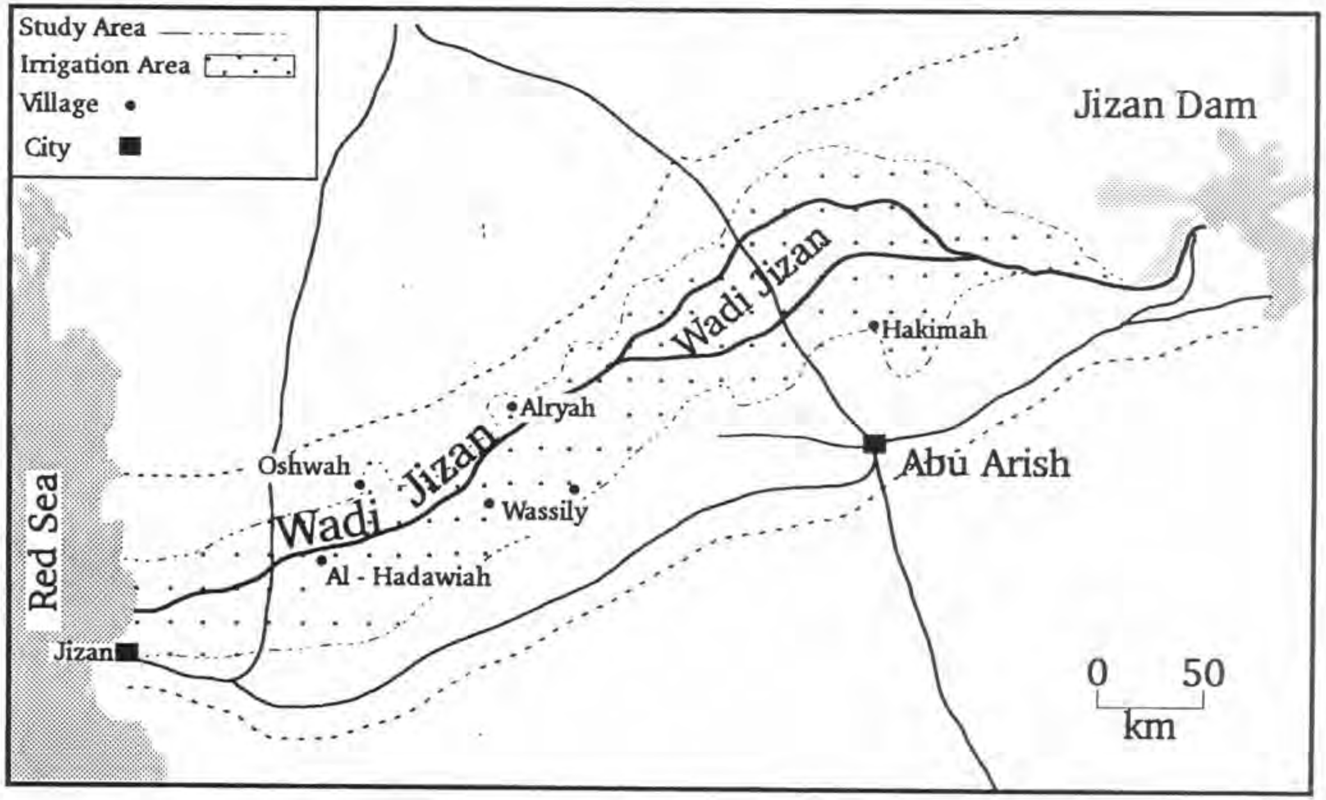
Wadi Jizan is characterised by frequent floods originating from the Asir mountains. The number of floods vary from 15 to 35 per annum with a volume of 0.5 to 10 mcm per flood. The average surface flow is around 80 mcm/annum (MAW).

Figure 6.16 shows the Wadi Jizan irrigation development. The run-off flows downstream from Malaki Dam. It has 3.0×10^8 m^2 irrigated area and irrigable land of 8.0×10^7 m^2. In all 1,520 km of main, sub and lateral canals were built, along with 1,320 km of drains (MAW).

The Wadi Jizan Development Plan was produced with three broad aims:

1. Regulating the extent of excessive flooding and storing the water in a reservoir.
2. Regulating water flow and distributing it to agriculture.
3. Generally encouraging agricultural development in the area.

Fig: 6.12.   Irrigation in Wadi Jizan Area



The Wadi Jizan project does seem to have experienced a large degree of success with an apparently thriving research and development programme, and irrigated area of around 30,000 acres (MAW).

Work on the construction of a dam in Wadi Jizan was completed and the project was inaugurated on 22 March 1971. The project includes construction of an irrigation network, submission of necessary recommendations for the development distribution of water among cultivators. On completion of this project increased the area of irrigable land in Wadi Jizan in around four years by 8,000 hectares (MAW).

As mentioned above the existing irrigation system involves reuse of water from field to field. Each time the water is reused, the salinity of the water increases for irrigation. Two irrigation methods were practised. One was surface irrigation with water flowing under pressure from artesian springs supplying large date plantations, rice and several other crops. The other method was surface irrigation through open ditches being fed with water pumped from springs and wells located mainly at higher elevations.

An alternative method consists of seven weirs, and twelve unlined and concrete canal regulators to control flood water. The whole scheme assumes full wadi flow with no storage after the full life of the dam has expired. Furthermore, the groundwater potential for irrigation is better than in all other four alternatives and there is a good area of land which could be brought under perennial irrigation. The scheme is judged sound technically and economically and the most suitable for the development of irrigation in Wadi Jizan.

The irrigation development of Wadi Jizan is through two separate contracts, one for the structures on the wadi channel and the main canals and the other for distribution channels, minor channels, canal outlets and field outlets. The two contracts were programmed so that the executive began upstream and proceeded downstream. The distribution network was to be completed at the same time as the main canals serving the same area so that development of the completed area could start without delay.

b. Irrigation in Wadi Dammad

Spate irrigation of agricultural land in Tihama Asir area, including Wadi Dammad, has been carried out for centuries. In this system, earth embankments called aqms are used to direct flood water to the fields. These aqms are temporary and could easily be destroyed by heavy floods.

Wadi Dammad is one of the important wadis adjacent to Wadi Jizan with similar soil and flood characteristics, and where spate irrigation with earth embankments is traditionally used for seasonal irrigation.

The area covers some 16,500 ha of land partly irrigated from flood water and easily accessible from Abu Arish in Wadi Jizan and from Sabya town.

Groundwater resources are estimated at 10.3 mcm/y. The annual available groundwater in the wadi is 12 mcm (MAW).

Electric conductivity is less than 2,000 microhms/cm which is found under the wadi bed, and the water is in general suitable for irrigated agriculture and for domestic use. Perennial irrigation is based on a unit area of 25 ha supplied by one well. The annual water flow of the catchment area is 59 mcm and the medium annual flow available is 50 mcm (MCM).

The surface water irrigation is used in the area, the suitability grading of the soil profile (see chapter 2 about soil) in the top two metres is identified as follows:

Class 1	2.960 ha
Class 2	4.100 ha
Class 3	1.680 ha
Class 4	2.470 ha
Total	12.210 ha

Nearly all the lands and water rights in the wadi are privately owned and some are Waqf land (for some groups no-one may use it without the owner's permission). Apart from the water rights, most of the land is communal tribal property or deadland. With few exceptions, individual land holdings are relatively small. There are some large family or clan holdings. The generous government agricultural subsidies encouraged farmers to expand their cultivated areas through land purchases or by acquisition of waste land on their boundaries.

The system of water allocation is laid down by local customary law which is acceptable to all farmers. Water is diverted out of the wadi bed by sand embankments called aqms and then passed from field to field (see Figure 6.2). Each aqm serves well defined areas of water rights in sequence, to allow water to pass down to the next aqm until all the fields are irrigated with the water available.

As a general principle, the government wishes to increase the production of cereals, livestock and vegetables so as to reduce imports. Wadi Dammad is one of the important cultivatable areas in Tihama Asir where studies were made for improving, controlling and distributing wadi floods and for exploiting groundwater by tubewells so as to contribute to increased agricultural production.

The objective of the development of Wadi Dammad is to improve the present traditional irrigation from surface water and to utilise groundwater for perennial irrigation, to grow better varieties of traditional crops and to introduce new crops, taking advantage of subsidies as well as using new farming techniques.

Spate irrigation is conducted by diverting water from a series of low diversion weirs with canal-head regulators and water is carried to the fields by a system of distribution canals with control structures. For spate irrigation it was proposed to construct five low diversion weirs and head regulators on two wadi beds for a flood of 3,200 m^3/sec, at weir 1. This would result in a small reduction in the floods for the weirs further down, so as to divert the floods to the fields without a storage dam, as done in Wadi Jizan. The justification for this approach was:

a) The economic life would be short (25 years) because of silting;

b) The irrigation system would follow closely the traditional pattern of irrigation in keeping with the traditional water rights;

c) Reduction of water losses through evaporation (MAW).

Three alternative schemes were proposed for spate irrigation. All the schemes divert the flood from the wadi by low diversion weirs and head regulators and convey the water to the fields by a system of distribution canals.

6.2 Livestock

The water resources have had a profound and adverse effect on livestock production through either direct control of, or the influence over, the type of land uses and quality and quantity of ranges. The competition for the use of the cultivatable land is fierce between crop and livestock farming. Subsistence crops and domestic animals were thrifty water users. The development breakthrough the 1985-1990 development plan led to a sharp growth in urban centres and the necessity for irrigated agriculture which demanded more water.

Sheep are of great economic importance. They are reared wherever there is suitable pasture and enough water.

Sizable ground water resources are available only in those parts of the country on sedimentary rocks. The western parts are dependent on runoff and shallow ground water resources.

The logical consequences of the limited water resources is the efficient and conservative use of these resources. The limited water resources have had a profound and adverse effect on livestock production either through direct control or through influence over land uses, and the quality and extent of ranges. Moreover, water from ground resources has a cost that reflects the two inherent characteristics of groundwater in the country. One is the variation in the regional depth of groundwater, hence sizable drilling, operating and maintenance cost. The second is the eventual exhaustion of fossil water as an economic proposition. Considering only these two characteristics it can be seen that water is costly. It was estimated by MAW that water from a flowing well of average depth of about 400 m cost about 10 cents U.S./m^3. In many parts of the country costly deep wells are left discharging fossil water for inefficient livestock uses.

Using the daily water requirements and the estimated livestock population, it has been calculated that the 1978 livestock water consumption was 37.7 m^3/day and future 1995-2000 consumption will be 46.8-50 m^3/day. On an equivalent *per capita* basis, existing 1978 and future 1995-2000 livestock water requirements are in each case, about 0.026 m^3/capita/day.

6.3 Domestic Water Demands

The domestic use of water has been increasing throughout the country, especially in the major cities. Some reasons for this are the increase in population due to high natural growth rates, migration from rural areas to cities and immigration from many different countries. These "relocations" are a consequence of economic growth financed by increasing petroleum revenues, thereby creating many new jobs and economic incentives, which attract people from both inside and outside the country to the cities. Another reason for the increase in water use is an amelioration of the standard of living among Saudi residents. This results in higher water consumption which in 1988 was estimated to be about 0.8 m^3/capita/day and which continues to increase. Furthermore, more houses are presently connected to the water network than have been in the past, thus increasing the stress placed on local water sources. All of these factors contribute to the increasing demand for water in the urban and rural areas.

The development of domestic water in KSA has been given priority to ensure potable water for people of KSA. It is vital that desalination plants and water towers are built. (The function of a water tower is to stabilise the head of the distribution network and equalise the pipe pressures.)

Work is in progress according to an established plan to develop sources of drinking water supply in KSA in order to meet the needs of the inhabitants of towns and villages, which are constantly increasing as a result of urbanisation and social progress. Several means are adopted to reach this aim. These include drilling of ordinary and artesian wells and bringing in spring water.

MAW is responsible for supplying water to cities and towns, although the actual operation of the installations is a municipal responsibility. In addition to supply systems in Riyadh and other main cities, new supply systems are scheduled for Tabuk and Abha, and studies are to be made of Al-Qunfudhah, Qarb, Sabya, Abu- Arish and Bayish.

MAW and Ministry of Municipal and Rural Affairs (MMRA) are carrying out water supply projects in the towns, villages and hejars in terms of priority. Water supply projects differ from village to village in respect of the geographical and geological location, as well as its site and population. These projects are implemented by Government finance. The citizens get the benefit from these projects free of charge. The government has so far drilled for this purpose more than 600 tape and hand dug wells. The MAW carry out the maintenance of the projects after their construction.

In the KSA urban area where population densities are substantially in excess of rural values there is a greater demand for water. Whilst it is important to have priorities in an ordered approach to reaching a water policy, it is very important to take into account both the qualitative and quantitative aspect of the water use. The accompanying chart indicates the relationships between priority and quality.

Water importing is in most cases equivalent to international inter-basin transfer and the construction of a pipeline for such an inter-basin transfer, usually of surface water, has the unmistakable attraction of proven technology. If the source is indeed surface water it is likely that after a feasibility study a reasonable quantification of a hydrologically reliable source and usable cost estimate can be prepared, together with a description of water quality fluctuation.

The domestic use demands for fresh or potable water, biological purity and sterility is a first priority. Industrial processes also require water with a minimum dissolved solids, often even purer than drinking water.

The cities' private and public garden water demands use potable water in large quantities while the rural water demands are such as to require substantial abstractions from the local aquifer. City distribution networks facilitate the unification of water charges and remove the presently existing order of magnitude range.

However, such a modern system, incorporating dial water meters, calls for a very regular method of billing for water used. Differential charging for water is often discussed in the context of checking the total demand placed upon the distribution network. This argument, however, is in the opinion of some of doubtful validity in conserving water and could result in people using insufficient water to maintain cleanliness to both the personal and domestic levels with consequent damage to public health.

Municipal water needs in KSA have been increasing at a fast rate and are expected to grow at a much higher rate than ever during the next few years. Unless some other source of water is developed, this entire increase will have to be met by taking water that could be used in agriculture, with a resultant loss in agricultural productivity, a declining level of employment in this sector and lower income of farmers who constitute the majority of the population and probably further desertion of the countryside for the cities.

The rise in water consumption in large cities such as Makkah, Riyadh and Jeddah is partly already the consequence of the increasing municipal water supply. Although historical data on municipal water supply and demand are lacking at present, nevertheless, one can expect the water consumption in the growing cities (at a rate of about 8% per annum) to grow more rapidly than that of the smaller towns and villages. This assumption is based on the fact that the supply of water in the large cities is undoubtedly more lavish than the supply in the smaller towns and villages, where the water distribution system is operated manually by more primitive means than in the cities, discouraging heavy water usage.

The cities of Riyadh, Makkah and Jeddah are an example of the major cities in Saudi Arabia which are experiencing a spectacular increase in their demand for water. Many other cities and small towns in Saudi Arabia are experiencing similar problems resulting in water shortages. To partly meet the water needs, many development projects have been undertaken to supply some coastal towns and selected inland towns with sea water. Brackish water treatment is also being practised to desalt fossil groundwater. Generally, most of the cities and the villages take their water from groundwater.

Since the 1970s, a spectacular growth in the urban population has occurred throughout Saudi Arabia, but particularly in the large cities. With rapid urbanisation, it has become increasingly difficult for local sources to meet the rising demand for drinking water. Water demand in the largest urban centres rose more than 200% between 1980 and 1990 to a total of about 870,000 m^3/d (MAW).

The augmentation of the existing source of potable water supply in different towns and cities of Saudi Arabia, and the improvement or replacement of the water networks, have been major objectives of the Ministry of Agriculture and Water Resources in the increased urbanisation and rising population in these towns and cities. A lot of the projects have already been executed while others are in different stages of implementation.

Urban water supply, which remains a focus of government policy, has been increasing rapidly, with the drilling of wells and implementation of desalination projects. Although there has been a considerable increase in urban water supply, there are still shortages in some urban areas as a result of the steep rise in demand. The question has, however, received, and continues to receive, maximum budgetary appropriations. It is hoped that in the future shortages will be virtually eliminated.

Jeddah

The annual consumption for 1985 has been estimated at 32mcm, with peak daily requirements of 102mcm/d.

The pipelines coming from Wadi Fatimah have a maximum discharge of 1.070 l/sec, corresponding to a maximum daily output of 92,000 m^3/day. Since there is a deficit of water in the supply zone, these pipelines are used for a continuous initial discharge of 334 l/sec (28,800m^3/d), of which 298 l/sec (25,700 m^3/d, or 9,400,000 m^3.y) reach Jeddah and 36 l/sec (3,100 m^3/d or 1,100,000 m^3/y) are supplied to small villages along the way. The ratio of utilisation being 0.86% daily output corresponds to an actual total output of 25,700 x 360 c 0.86 = 8,100,000m^3/year.

The pipelines coming from Wadi Khulays has a maximum discharge of 400 l/sec equivalent to a daily output of 34,500 m^3/d, and to an actual total output of 34,500 x 365 x 0.86 = 10,800,000 m^3/y. At present this pipeline is used for a continuous output of 188 l/sec (16,200 m^3/d) which corresponds to an actual total output of 16,200 x 365 x 0.86 = 5,100,000 m^3/y. The deficit can be covered in this way:

a. with a further withdrawal from Wadi Fatimah, which is only possible by reducing either agricultural uses or the supply to Makkah;

b. with a further withdrawal from Wadi Khulays up to a maximum total of 14,100,000 n^3 if the present amount used for agriculture is to be maintained, or up to a total maximum of 30 mcm/y if the use of water for irrigation is to be reduced partially or totally;

c. with further extension of the desalination plant with units capable of supplying 3,050,000 m^3 each annually.

The water supply for Jeddah depends on three possible resources: Wadi Fatimah, Wadi Khulays and desalination. Wadi Na'man has been excluded because its geographical position implies its use for Makkah rather than for Jeddah.

Makkah

Consumption for 1985 has been estimated at 19 mcm/y, with peak daily requirement of 69,000 m^3/d. The pipelines from Wadi Fatimah at present have a maximum discharge of 12,000 m^3/d, and since they are used with a uniform rate of output they provide about 4,350,000 m^3/y.

The pipelines from Wadi Na'man is also used with a constant discharge of 6,000 m^3/d and a total output of about 2,200,000 m^3/y. With respect to the present availability, the major requirement for 1990 will be 1,245,000 m^3/y whereas the peak daily requirement will increase to 51,000 m^3/d.

The deficit can be covered as follows:

a. with further abstraction from Wadi Fatimah although this will only be possible by reducing agricultural uses and/or the supply to the city of Jeddah;

b. with further abstraction from Wadi Na'man;

c. with further extension of the desalination plant with units capable of supplying 2 mcm/y.

The Makkah water supply remains dependent on three possible resources: Wadi Fatimah, Wadi Na'man and desalination.

6.3.1 Riyadh Water Plan

Riyadh is the capital of Saudi Arabia, and the people of Riyadh relied for many years exclusively on the limited amount of water tapped from shallow wells in Wadi Nisah, Wadi Namar and Wadi Hayir. This was possible because of the low population of Riyadh. The volume of this water because of the difficulty of drilling the wells by traditional means. The water that was available, however, was of good quality with total dissolved solids (TDS) of about 500 ppm. The range of depth of the shallow wells is about 60m to 80m (El-Khatib, 1980). By using new technological means of drilling wells and pumping water, the level of water in most of the shallow wells dropped as a result of over-extraction. Another problem related to using water from shallow wells is contamination by sewage water due to the existence of poor sewage networks. Both water demand and consumption have increased sharply during the last decade in

Riyadh as a result of rapid population growth. Several factors have contributed to this growth:

1. Riyadh is the capital city and the main administrative and commercial centre of Saudi Arabia.

2. There have been many recent construction projects in Riyadh because of Saudi Arabia's five year development plans initiated in 1970.

3. There are a great number of opportunities for employment in Riyadh.

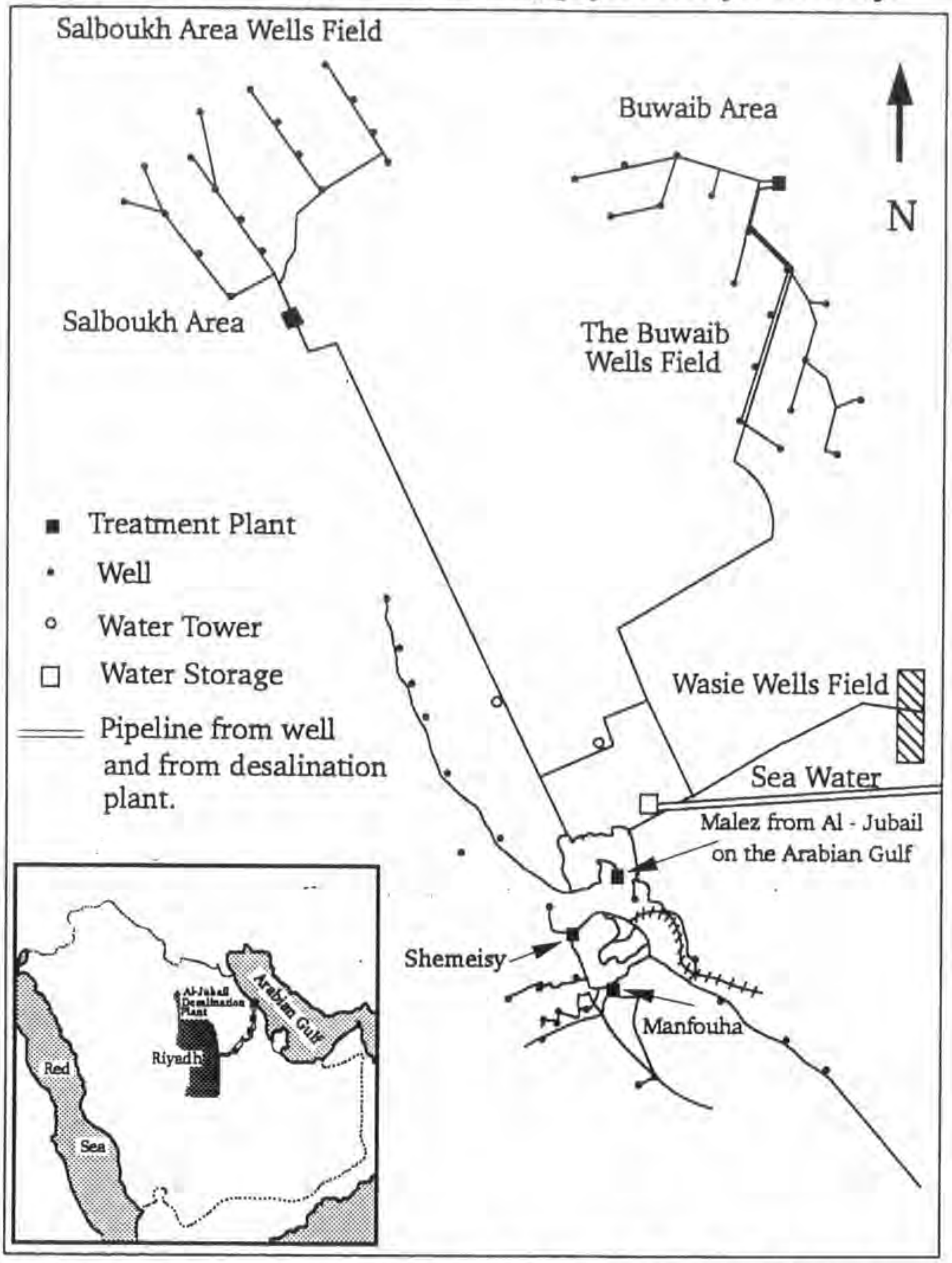
The above factors motivated many people to migrate to Riyadh from the rural areas of Saudi Arabia. Furthermore, an improved standard of living, higher levels of education, and a very high birth rate have all contributed to the sharp increase of water consumption during the last decade, an increase that will continue into the future. Consequently, additional water supplied are needed to meet the growing demand.

The inhabitants of Riyadh are provided with municipal water derived from a variety of sources, some as distant as 450 km from the city. Because the government had completed a series of monumental engineering and construction projects, a dependable water supply had become available to meet the anticipated water demands created by continuing sharp population growth in the city.

At present, as Figure 6.13 shows, Riyadh obtains various amounts of its water from the following sources:

1. Traditional shallow groundwater aquifers. These are the main water resources when the first deep well was drilled in Riyadh, tapping the Minjur Aquifer. Shallow aquifers include Wadi Nisah and Wadi Hanifah and its tributaries.

Fig. 6.13. Major Water Supply for Riyadh City.



Sources: The Annual Report of Riyadh District Water and Sewage Department [1985] and M A W.

2. Deep ground water aquifers. The two main aquifers supplying water to Riyadh are Minjur and Wasia. The Minjur was the source of more than 80% of all water used in Riyadh until 1979. Wasia began supplying the city with water in 1981. Deep aquifers are the principal water sources, although analysis was done to compare Minjur and Wasia.

3. Desalination. The mammoth Jubayl Desalination Plant II on the Arabian Gulf began pumping water to Riyadh in 1983 through twin 60 inches pipeline with a capacity of 415,000 m^3/day/line.

4. Sewage effluent: Although it does not contribute greatly to Riyadh's municipal water supply, part of Riyadh sewage is treated and reused for irrigation and for cooling at Riyadh Refinery.

This is the biggest and most important project and has passed through several stages. The plans of this project and the study and construction programmes, as well as future anticipations, reconsideration, evaluation and plan modification during construction, were made in the light of social economic and development variables of the people of the city because population development in the city exceeded all expectations. In 1951 the population was about 80,000 persons and in 1963 not more than 160,000, while in 1986 it increased to approximately 1,630,402 persons. The increasing demand on water was associated with several studies which started in 1948 and have continued to date being undertaken by different international organisations, individuals and consulting companies. Riyadh is supplied with water from many sources, as follows:

1. Shallow Groundwater Aquifers
2. Boyadh Aquifer in Wadi Nisah (Deep Groundwater Aquifers)

1. Shallow Groundwater Aquifers

The water of this aquifer is utilised only for irrigation and agricultural purposes.

Water from shallow wells is generally of good quality, but is sometimes exposed to contamination. Water is obtained from the following aquifers.

Wadi Nisah of the Riyadh Formation is overlain by wadi alluvium thus creating favourable recharge conditions. Ground water from here has been used to supply Riyadh. Infiltration is in the order of 2-6% of the rainfall. Water quality is favourable and contains dissolved solids about 500 ppm.

The major water sources that supply Riyadh are in the Minjur Sandstone, some 400 m thick and over 1,000 m below ground level. Production from the Minjur Aquifer has been increasing. Water was tapped from 14 wells with total production of 19,221 mcm.

The Minjur Aquifer is, at present, largely used both for Riyadh's water supply and for supplying the central Najed towns. It is formed of sand and fairly coarse consolidated quartzitic sandstone which represents 70-80% of the total thickness. The rest consists of thin layers of hard grey and brown limestone, coloured shale, conglomerates with limestone and dolomitic cement and occasionally gypsum, irregularly distributed throughout the entire thickness of the formation.

2. Biyadh Aquifer in Wadi Nisah

Begun in 1979, this project was started, and it takes water from the Minjur Aquifer. It is located at Riyadh, and supplies the city with treated water pumped from eighteen deep wells. Production from the Minjur Aquifer has increased dramatically since the first deep well was drilled.

This aquifer produces about 79,000 m^3, which is pumped for treatment in Shemessy through Hayer station.

Wadi Nisah of Riyadh formation is overland from here and has been used to supply Riyadh. The wadi is a long, narrow garden of limestone and marly limestone formations which cut through the Tuwiq Mountains in an east to west direction some 40 km south of Riyadh.

Infiltration is in the order of 2% to 6% of rainfall. Water quality is favourable and the content of dissolved solids is in the order of 500 ppm.

Drawing water from the Manjour aquifer of Riyadh. This water is treated in three treatment reservoirs located at three separate places in the city:

a. Malez project, capacity 24,000 m^3/day.

b. Shemessy project, capacity 36,000 m^3/day.

c. Manfouha project, capacity 88,000 m^3/day.

Salbukh Water Project is some 50 km north-west of the city of Riyadh, where 16 deep wells were drilled through the Minjur aquifer to supply some 60,000 m^3/day of additional domestic water to Riyadh which comprises wells of an average depth of 1500 m, including all pumping equipment. Also, water treatment plant with apputenant tanks and 21 MW power stations consisting of:

a. Cooling towers to reduce water temperature from 60°C to 30°C.

b. Precipitation basins where water is dosed with chemicals to cause precipitation.

c. Sand filters.

Village pipelines connect the wells to the treatment plant and to the city of Riyadh, totalling 160 km with diameters varying from 300 mm to 1100 mm, and a reservoir with a capacity of 20,000 m^3.

Buwayb Water Project is some 65 km north-east of Riyadh where 18 deep wells were drilled through the Minjur aquifer to supply Riyadh with some 80,000 m^3/day additional treated water.

The project consists of wells between 1500 m and 2100 m deep, including the pumping equipment, a treatment plant with tanks consisting of:

a. Cooling tower to reduce the temperature from 60°C to 30°C.

b. Precipitation basins, where water is dosed with chemicals to cause precipitation of minerals.

c. Sand filters to remove the precipitation through reverse osmosis.

The reservoir to collect treated water with a capacity of 25,000 m^3, with a 90 MW power station to generate power for pumping water and supplying the village with electricity.

Pipelines include: from well field to the treatment plant 500mm diameter; pressure main pipeline of 1000 mm diameter; gravity main pipeline of 900-1100 mm diameter. The pipelines connecting the wells to the treatment plant and to the city, and reservoir with a capacity of 15,000 m^3 at the city.

Wasia Water Project lies 110 km from Riyadh. It includes 62 wells of average depth. It has a water treatment plant with its apartments, village, tank 150,000 m^3, in addition to other ground and elevated tanks. The water is conveyed to Riyadh through two parallel pipelines each 1100 mm in diameter.

This project was begun in 1981 and consists of sixty-two deep wells. It produces 200,000 m^3 of water daily. The depth of the wells range from 400 m to 550 m. They contain brackish water which has to be treated (MAW). The formation recharge is very limited compared to the output, with the rapid growth rate of Riyadh exceeding the planners' anticipation, additional water supplied are needed to supplement the underground sources in order to meet the city's growing demand for water.

The piezometric levels for the Wasia is very deep close to the outcrop, over 200 m west of Ad Dahna and reaching 285 m at Rumah.

The quality of water in the Wasia Aquifer is relatively good over the entire Khurais oil field, except in the north of Jaham and Ma'agala. It ranges from 1,000 to 15,000 ppm total dissolved solids (TDS). Due west of Khurais and west of Ad Dahna closer to the outcrop, the water quality reaches 2,500 ppm over a considerable distance.

Al Jubail Water Project is a seawater desalination plant on the east coast of the KSA. The water is treated and fed to Riyadh by pipeline and pumping stations (see Chapter 5).

The Ministry of agriculture and Water (MAW) constructed several tanks and pumping stations in Riyadh to provide the proper pressure for dealing with the water supply.

In Malez Plant, water is pumped from four deep wells to eight cooling towers so as to reduce the water temperature to around 25 to 35°C, and it is then collected in reinforced concrete ponds. The water is then passed to filtrators and is dosed with chemicals to cause precipitation. The precipitators are equipped with circular structures containing inlet devices, mixing and settling compartments, sludge concentrating sumps, effluent troughs etc., all built from prefabricated concrete, and adjacent to the main building.

The plant includes the following: five horizontal centrifugal-type pumps complete with electric motors; suction and delivery pipework complete with fittings for the pumps; from the joint at the outer well on the incoming fresh water 800mm diameter main from the reservoir to the corresponding joint on the outgoing 60mm diameter pressure main and the 600 mm diameter branch thereon; 600 mm diameter filtered water collecting main from the end of the filter gallery through the pump room extending to the joint at the outer wall of the pumping station.

Shemeisy Plant is supplied with water from one well to two cooling towers and the water is then collected in reinforced concrete ponds, together with cooled water from the Hayir Pretreatment Plant. Water is then taken to four precipitators where it is dosed with chemicals to activate the precipitation process. The precipitators include circular structures with inlet devices, mixing and settling compartments, sludge concentrating sumps, effluent troughs etc., built from prefabricated concrete slabs. The water from the precipitators passes to two-stage filters similar to those of the Malez treatment plant adjacent to the main building. The main building has the same arrangements as that of the Malez plant.

The plant includes the following: seven horizontal centrifugal-type pumps complete with electric motors; suction and delivery pipework complete with fittings for the pumps, from the joint at outer wall on the incoming 800 m main from the reservoir to the corresponding joint on the outgoing 800 mm pressure main at the end of the filter gallery.

In Manfouha Plant water is supplied from two deep wells and cooled in four cooling towers. The water is then taken with the cooled water from the pretreatment plant at Hayir to four precipitators equipped with the usual structures. After treatment, water from the precipitators passes to two-stage filters similar to those of Malez treatment plant, adjacent to the main building.

The shallow aquifers of the Riyadh region that are used for the city's water supply are those at Wadi Hanifah and its tributaries, Wadi Nisah and the Jubaila limestone formation. The current Riyadh water supply from the shallow aquifer is nearly 56,000 m^3/day, or 18% of the city's water consumption. Most of the city's shallow water resources are obtained from Wadi Nisah, which amounts to 38,000 m^3/day, or 68% of the overall shallow aquifers. The Jubaila limestone formation is no longer a source for city domestic use because of its contamination with city sewage effluent.

Unfortunately, their water contribution to Riyadh's water supply is minimal because of the poor quality of water stored in the aquifers.

The shallow aquifers can significantly contribute to Riyadh's water supply with some modifications of their use. More benefits from the shallow aquifers also can be accomplished if groundwater withdrawal and use management are assigned to all ground water users.

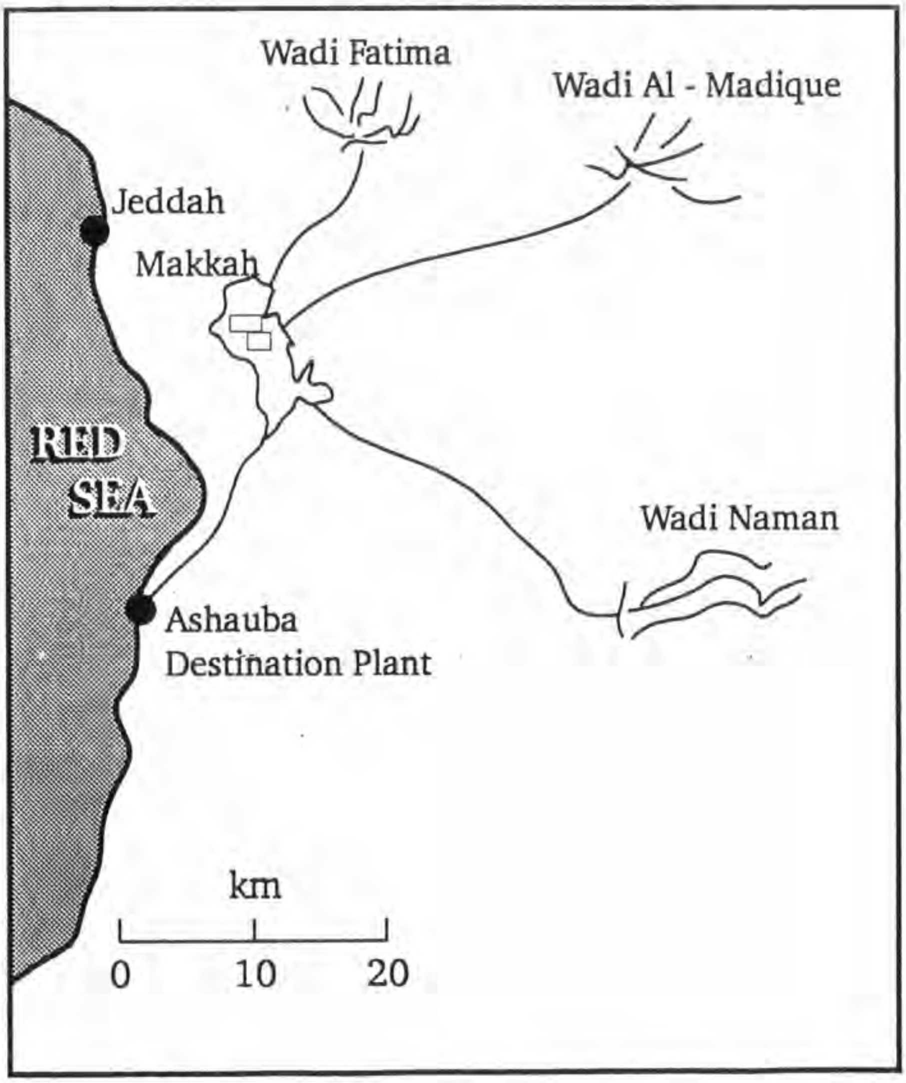
6.3.2 Makkah Water Project

Makkah's oldest water resource is the Zam Zam well. It is said to have started spontaneously from the Wadi Al-Abrah. The well is still used by the pilgrims as a source of water supply.

Subsequently new wells were dug and water was brought into the Makkah in stone channels from springs in the higher reaches of Arafat, such as Al-Zihar, Al-Asqalany and Ju'aranah. In the city for many centuries, these ancient water supply systems were sufficient, although from time to time new wells and aqueducts were constructed as old wells became depleted, agricultural expansion was planned, or there was an increase in the number of pilgrims. As a result of increasing demand, hundreds of new wells have been dug around the city to provide additional water. The population increasing in the city has increased the demand for water. The total daily water demand is in the region of 55,020 m^3. The total daily supply of water is 21,600 m^3 - a deficit of 33,420 m^3/d (MAW).

The water for Makkah was mainly supplied from wells in the alluvial deposits of the Wadi Naaman and the Wadi Fatimah. The Mudiq system built in 1962, and the

Fig. 6.14 Water Supply for Makkah



Source: MAW

Aziziah system, are fed by groundwater from the Wadi Fatimah. Withdrawal rates from them were 4,600 and 5,000 m^3/day, respectively. The water use rates for Makkah had increased to 9,600 m^3/day from Wadi Naaman and to 30,000 m^3/day from Wadi Fatimah (MAW).

The total estimated recharge from all wadis supplying the city of Makkah for domestic use and for agriculture is in the order of 80 mcm/y (MAW).

Details of Makkah's water supply, seen within the social and economic setting of the region and Saudi Arabia as a whole, are examined below.

The water supply to Makkah should, in the short term, be from groundwater, that is by increasing supplies from Wadi Naman and its tributaries, and demand by possible increased supplies from the upper reaches of Wadi Fatima. In the long-term, a more radical solution may have to be found (e.g. desalination). Groundwater continues to be used as the main source of supply to Makkah. However, a major role of groundwater in the reserves to deal with peak demand as during the Hajj, necessary groundwater extraction and delivery installations should be so maintained as to be ready to deal with such peak demands.

The average urban specific consumption of water is 3715.2 m^3/d, that the domestic demand for water is around 59 mcm/y and industrial water demand is around 5 mcm/y.

The potable water was stored in 12 reservoirs in the pilgrimage area. The reservoirs are at Arafat and Muzdalifah, north-east Makkah. Ten smaller reservoirs had an additional storage capacity of 35,000 m^3. In addition, 112 water trucks were placed in the area to supply water to the pilgrims (MAW).

This project is more important than any other because is serves the Holy City for Muslims and the Hajj (pilgrimage). The project had two stages. The first stage was completed, and involved drilling nine wells and delivering water from some previously known wells as well as newly discovered sources to the city's water supply system. The second stage has been put out for proposals. It includes the construction of the nine water reservoirs which were built with a capacity ranging from 300 m^3 to 80,000 m^3, three of which would be built in Makkah and six in other Hajj areas, the drilling of 24 experimental wells and the installation of nine water pumps (Figures 6.15, 6.16).

In order to assist the pilgrims with their ritual ablutions, water basins were installed throughout the Hajj area. With close to two million pilgrims participating in the ablutions before each of the five daily prayers, a considerable volume of water passed through the faucets. This arrangement reduced the ceremonial consumption of water by about 75%.

Estimated and projected overall water use figures are 10,368 and 12,096 mcm/pilgrim/day for the years 1990 and 2000 respectively.

During 1988 Makkah obtained drinking water from desalination plants for the first time (see Chapter Five, section 1). Also main and distribution pipelines of various diameters 100-1400 mm were constructed. The total length of pipe constructed exceeded 600 km, and more than 140,000 house connections were made.

6.3.3 Jeddah Water Project

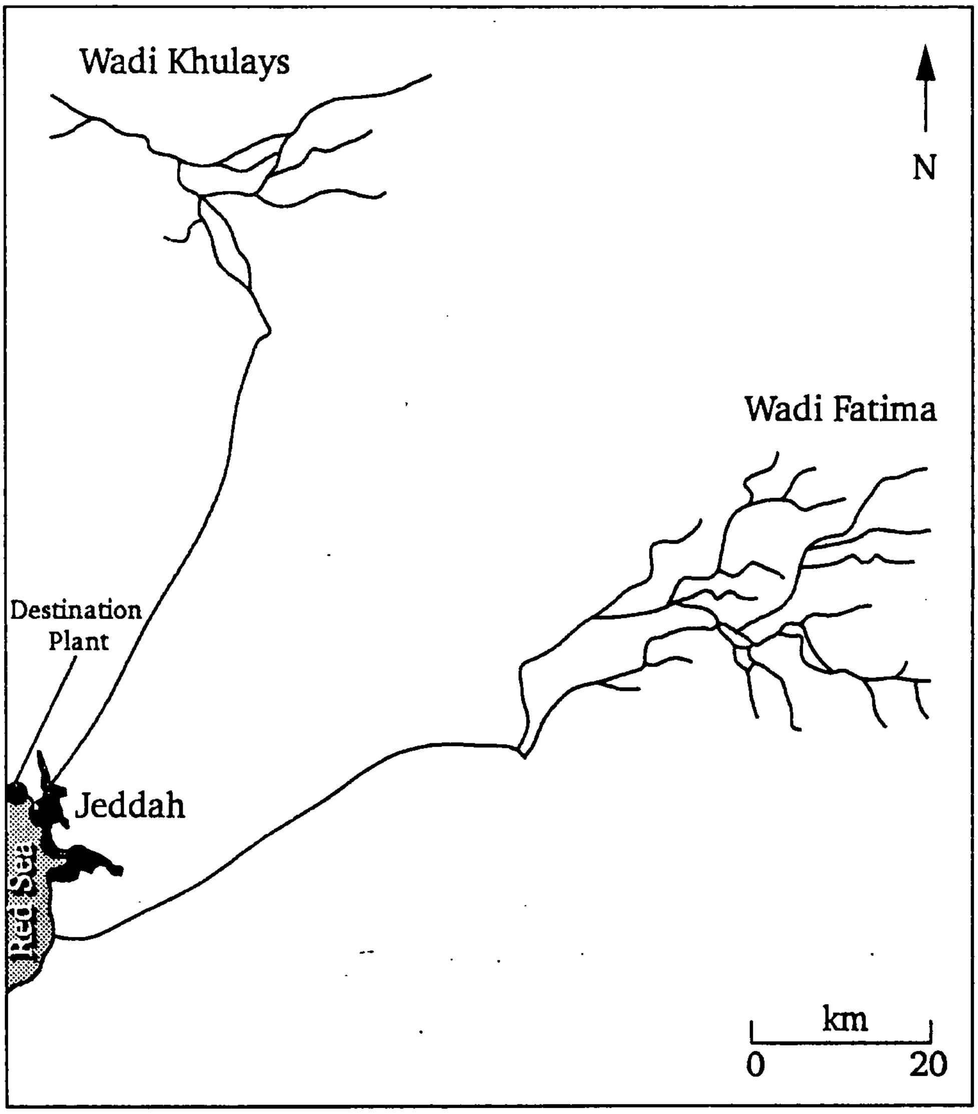
Jeddah City is the main port and commercial centre of Saudi Arabia on the Red Sea coast, where thousands of pilgrims arrive every year to visit the Holy Cities. One of its main problems is shortage of potable water.

In the 1940s, 90% of Jeddah's water was drawn from wells or delivered by bucket and by truck. Later, in the 1950s, the city began to draw water from two sources: Wadi Fatimah and Wadi Khulais.

Figure 6.15: *Water reservoir in Mekkah for pilgrims*

Figure 6.16: *Water reservoir used for houses at main road between Mekkah and Jeddah*

Fig. 6.17 Water Supply for Jeddah



Source: MAW

The recent growth of Jeddah's population is following:

1. Saudi Arabia's largest airport is in Jeddah, therefore, many foreign companies are located there.
2. The high birth rate within the city, there has been increased immigration from the rural areas and from outside the country to Jeddah because of good job opportunities.
3. Like Riyadh, Jeddah has undergone a substantial increase in construction under Saudi Arabia's five year development plans.

The growth in population, together with economic and educational improvements, has led to increased demand for water. A further demand is placed on Jeddah's water supplies every year when tens of thousands of pilgrims pass through Jeddah during the Haj season en route to Makkah. The water tapped from Wadi Fatimah and Wadi Khulais eventually become insufficient to cope with the growing need. Therefore, in the late 1960s, the government decided on the expensive solution of desalinating sea water to overcome the city's water supply problem.

Wadi Fatimah

Located 55 km east of Jeddah, Wadi Fatimah first supplied with Jeddah with water in 1947. It covers an area of about 4,400 km^2. It is anticipated that when Jeddah has sufficient alternative water supplies. In recent years more dug wells have supplied Jeddah with between 30,000 m^3/d to 40,000 m^3/d from this wadi (MAW). Present studies reveal that there is a great decline in the groundwater levels because many wells have gone dry from over-extraction. The agricultural land near the wadi has suffered. The average decline of the groundwater level in Wadi Fatima is about 70 centimetres/month due to the limited recharge.

Wadi Fatimah supplies water to Jeddah. The water is conveyed to Jeddah through two asbestos-cement pipes, to nine reservoirs, with a total capacity of 65,000 m^3, situated 14km along the Makkah road. After being chlorinated, the water is carried by gravity to the city through mains and sub-mains of asbestos-cement pipes and distributed to laterals and buildings mostly through galvanised steel pipes which are now partly corroded or blocked.

MAW drilled 49 wells with an average production of 40,000 m^3/day. As they were keen to develop farming in the Wadi and avoid water depletion in the aquifer, MAW constructed one of the biggest dams in the KSA for storing water to recharge the aquifer in the Wadi.

Wadi Khulais

Wadi Khulais is about 113 km north of Jeddah and it covers about 5,200 km^2. The wadi supplies Jeddah with approximately 10 mcm/y. This leaves the basin with about 15 mcm/t, to be used for agriculture, an amount insufficient to irrigate the cultivatable lands. Khulais faces a continuous depletion of the water table because the groundwater is being overdrawn (MAW).

Wadi Khulais supplies Jeddah with water conveyed through an 800 mm asbestos-cement pipe to a point about 32 km north of Jeddah where a large filling station for tankers has been established for onward transport of the water to the city.

For supplying additional water to the city of Jeddah, the MWA is conducting detailed investigations of the Wadi Khulais basin covering an area of about 9713 km^2 with the following main objectives:

a. Investigating the present situation of both surface and groundwater resources and their inter-relation.

b. Ascertaining direct and indirect causes of the decline of groundwater levels and increase in salinity.

c. Assessing the possibility of improving utilisation of the water resources of the basin.

In the light of the investigation, the consultant found that there has been a great drop in groundwater levels due to the extraction of groundwater for Jeddah's water supply. The result of the hydrological investigation clearly indicates that the maximum development of Wadi Khulais basin can be reached through water conservation and artificial recharge. The construction of dykes on the Wadi Khulais plain and the construction of a dam in the lower reaches of Wadi Murwani will ensure additional recharge and provide flood protection. Studies indicated that it is preferable to keep water resources for irrigation and provide drinking water to the city of Jeddah by desalination of sea water.

Water is taken from 37 wells. The average production is 30,000 m^3/day. MAW has conducted a study for the construction if Khulais Dam. The dam has been designed and will increase water storage in the area to be used for agricultural development and domestic purposes.

Jeddah Water Plan

The three sources of water supplying the city at present are: Wadi Fatimah, Wadi Khulais and the desalination plant. The total replenishment of both Wadi Fatimah and Wadi Khulais is 61.5 mcm/d of which 32.6 mcm/d is used for irrigation.

Investigating the possibility of further resources for Jeddah, MWA concluded that the only additional source of water for Jeddah is sea water. The increased water supply to Jeddah is based on desalinated seawater, while the groundwater contribution should be decreased as the overdraft (some 13 mcm/y on the groundwater reserves to the city) on Wadi Fatimah is reduced and finally eliminated. Groundwater is an appreciable (14 to 15 mcm/y) but auxiliary source of supply to Jeddah.

The government decided to expand the capacity of desalination plant by a further 17.2 mcm/d, and necessary action has been taken in phase 4 to expand the capacity to 137.8 mcm/d.

The Jeddah water supply was withdrawing about 24.8 mcm/year from these two wadis. This withdrawal was severely depleting the water supply needed for agriculture. Results from a number of studies determined that water withdrawals from these wadis for municipal use should be curtailed in favour of water use for agriculture, a change that led to the desalination plant to make up the loss to Jeddah.

Existing supplies of water from desalination plants and well fields, totalled 208 mcm/y.

A rapid growth in Jeddah's population is expected to continue until the end of this century. Therefore, expanded water supply through desalination will be required in order to meet future water demands.

6.3.4 Domestic Water Demands in Tihama Asir

Traditionally, the main source of water for the inhabitants of Tihama Asir has been hand-dug wells in local wadis such as Wadi Jizan. With urban growth an additional source of groundwater was obtained from recharge runoff. It supplies water from a drainage basin, and receives an annual average precipitation of about 238 mm. The demand water of ?1,794 mcm, that is return flow will be expected to be tappable from about 25% of available runoff or recharge and from aquifer. The Tihama Asir is more promising compared with the wadi, where over extraction from aquifer seems to be prevailing. In fact the potential water in Tihama Asir is ?1,792 mcm but water requirement is ?1,328 mcm. Regarding the water requirement for municipal water supply, the average use is estimated to be 0.15 m^3/person/d, and the total population in the area will increase in the year 2000 to between 998,000 to 1,225,000 (MAW). Thus the total amount is roughly estimated at 70 mcm, including allowance of 30%.

Water consumption per person per day is at present very low due to the way of life which is geared to water scarcity. The Jizan project is based on the daily consumption of 0.1 m^3/capita, but according to the field survey, each household consumes approximately one ten per months in the area's cities. With changes in the way of life and the improvement in the standard of living, this demand will undoubtedly increase rapidly. The supply capacity of Jizan Dam is said to be enough for 60,000 persons (MAW). Thus, finding and developing more water resources and their efficient use are the most important problems for the cities.

The domestic water include the design, construction and supervision of drinking water supply networks including the drilling of wells.

The methodology used for the values is based on two linear regression models both of which are functions of several explanatory variables. Urban demand is related to:

- The previous urban demand.
- The annual increase in school involvement.
- The annual increase in the number of houses connected to the water system.
- An indicator, a variable.

The use of such a variable, although simple and expedient, throws doubts on the results in case there would be any unexpected increases in the revenue from oil (German Consult Reports, 1979).

The investigator selected an approach that combined population estimates and the water supply *per capita* demand rated, each of which is available on regional basis. This ratio varies considerably from one place to another. It is concluded that the aggregate national division be 40% domestic and 60% horticultural use. See Tables 6.4 and 6.5.

In Tihama Asir there are six important cities, including Jizan, Sabya and Abu-Arish. These cities are going through a phase of rapid population increase. This expansion in population is accompanied by continuous development of industry and a constant improvement in the standard of living.

The socio-economic distribution of water demand for Tihama Asir in 1991 is indicated by four categories of accommodation: villas, flats, low quality housing (LQH) and shanties. At present the average urban daily specific consumption of water in the area is some 77 m^3. In view of the use of private wells within the area for garden irrigation, essential water demand has been assessed at 25 mcm/year on the high estimate and 11 mcm/year on the low estimate. Public garden water demand has been assessed at 2 mcm/year on the high estimate and 1 mcm/year on the low estimate. Industry and other users will be assumed to use 2 mcm/year and 3 mcm/year respectively on the high and low estimates. Private garden watering demand has been assessed at 3 mcm/year and 2.8 mcm/year respectively on the high and low estimates, as shown in Tables 6.4 and 6.5. Water demand is determined by the consumption of the various types of user. The totals are usually aggregated and reduced to a *per capita* consumption of around 55.5 mcm/year, the growth trend in *per capita* water consumption the basis for the demand water the estimate that the average specific consumption levels. The urban average specific demand is increasing from 36.5 mcm/year. Tables 6.4 and 6.5 show 1991 projections, increasing from 1971 at the average annual rate of half per cent. Maximum demand (or peak load) is estimated as a result of previous urban experience in the city, taking into account the greater sizer of the water undertaking and the increased water use by the population range under discussion.

The industrial allowances are estimated to result in a requirement for 3 mcm/y. The private garden water is approximately the area and average size of the regular irrigation is 260 m^2. These private garden water demands are 8.7 mcm/y. Other water demands including institutional and municipal are estimated at 7.3 mcm/y.

Total water demand for Tihama Asir cities is related to a number of variables. These include population size and growth rate, distribution of population with regard to social and economic consideration and *per capita* consumption growth. This indicates the growth trends in *per capita* water consumption from 1970 to 2000 and forms the basis for the demand projections. In projections for 1991 it was estimated that the following average specific consumption levels will have reached: villas at 350 mcm, flats at 280 mcm, large houses at 150 mcm and shanties at 60 mcm; weighted essential urban average specific demand is 186 mcm, an increase of 2.33 since 1971 or just under 4.5% per annum. A socio-economic survey is conducted to estimate the urban and rural population water use. The total water use is 55.5 mcm/y as shown in Table 6.4, and Table 6.5 gives high and low estimates for the essential water demand for the socio-economic distribution of population in Tihama Asir. Four categories of accommodation are identified. The specific consumption of water in villa accommodation ranges hugely between 0.7 mcm/y and 6.1 mcm/y, presumably because of low and less constant occupancy. Consumption in large houses, with a more consistent occupancy than villas, ranges from 6.9 mcm/y to 4.4 mcm/y. Consumption in flats, on the other hand, with their higher and more consistent occupancy, ranges from 6.1 mcm/y to 12.2 mcm/y. In contrast, consumption in shanties is a mere 0.1 mcm/y due to lack of access to water. Weighted essential urban average specific demand is accordingly taken as 36.5 mcm/y.

Table 6.4: *Urban and Rural Population Water Use in Tihama Asir by Type*

Type of Use	Annual Use (mcm)		
	Urban	Rural	Total
Essential	25.3	11.2	36.5
Industrial	3.0	Nil	3.0
Private Gardening	8.7	Nil	8.7
System and Network losses	6.1	1.2	7.3
Total	43.1	12.4	55.5

Table 6.5: *Essential Water Demand in Tihama Asir*

Demand Grouping	High Estimate	Low Estimate
Villa	6.1	0.7
Flat	12.2	6.1
Large house	6.9	4.4
Shanty	0.1	0.1
Total	25.3	11.2

The population size is not only growing but it has become increasingly urbanised which has a significant effect since, of course, urban dwellers tend to consume far more water than people living in the rural areas.

For example, the effect of urban expansion and modernisation in cities such as Jizan, Sabya and Abu-Arish in Tihama Asir and the introduction of modern buildings also heralded modern water supply systems, and all these factors have combined with improved standards of living to create an unprecedented demand on existing supplies thus creating serious problems. Much of the excess demand for water in Tihama Asir cities is the result of the spread of modern water supply systems, and in particular, the rise in the number of houses with piped water supply.

However, rapid urbanisation is taking place, which will in turn lead to accelerate the increase in demand for water. The expected situation in Tihama Asir cities is that the total consumption will rise from 28,800 mcm/annum in 1978 to 203,900 mcm/annum. Such a situation in Tihama Asir cities is similar to what is happening in many other KSA cities.

In the Tihama Asir area, the domestic water demand was 900 mcm/day in 1990 and it is estimated to be more than 2000 mcm/day by the year 2010. The industrial water demand was 350 mcm/month in 1990 and expected to increase to 550 mcm/month in 2010. These are the demands which are important according to the present situation since any proper water supply system must be geared towards providing water on demand and must be capable of supplying the amount of water likely to be needed. In comparison, the urban water demand in Tihama Asir is between 1980 and 2010 is likely to be from 180 mcm/day to 1273 mcm/day while the industrial demand is between 22 mcm/month to 320 mcm/month. If *per capita* demand does reach the level 1273 mcm/day by 2010 this will represent a 400% growth in *per capita* demand in a period of around 20 years.

The water used in Tihama Asir comes from Jizan's seven wells and from other local wells. The water is pumped to the town's water towers. The pipe network then distributes the flow to houses within the town and to public standpipes.

At present the average urban specific consumption of water in the area is some 0.077 m^3. In view of the use of private wells within the town for garden irrigation the belief is that the essential specific consumption is nearer 0.068 m^3.

Using the same essential specific consumption data for the various demand categories as for the other areas, the estimate of the 1995 essential specific consumption is 0.210 m^3, a 3.8-fold increase since 1975 or approximately 7% per annum. This rate is higher than for any industrial demand, large of small, irrespective of area or population served. In the Tihama Asir there is only a small industrial demand, using less than 0.050 m^3/day comprising of many types making a wide range of products. The water is taken from the public water undertaking.

In communities where there is no water due to over-exploitation of groundwater, MAW is transporting water to them by tanks and trucks, particularly to the range lands where no water is available.

The large groundwater reserves in the southern area show quite wide variations in quality. At Baysh the total dissolved solids is around 500 ppm and at Sabya it ranges from 800 to 1,200 ppm. Extraction of water from the sandstones is predominantly of salinity at less than 1,500 ppm.

The policy of the government is to provide water for domestic use to communities and villages scattered in Tihama Asir. The MAW is giving high priority to the drilling of wells either directly or through the letting of contracts to local and international contractors.

During 1985 the MAW started the execution of over 40 water schemes, and another 43 during 1987. There are some 60 villages with schemes in operation and it was expected by that by 1989, over 8 more schemes would be in operation, including the installation of motor driven pumps, and the construction of water towers as in Aiban and Al-Radha (Figure 6.18).

The wells in the region (Tihama Asir) are dug in or near the bed of the wadis. The conductivity between 600 micromhos/cm at 25°C and 1800 micromhos/cm at 25°C. The freshwater from the alluvial deposits of the wadis contains sodium and calcium in more or less equal quantities.

Regarding drinking water supply, all projects are executed by the private sector, which also conducts many operations and maintenance activities. The private sector include activities related to water conservation such as the introduction of applied technology in techniques of water-saving.

The private sector participates in numerous activities related to water sector. In the field of water resources development, all well drilling is carried out by private sector contractors.

The water sector comprises an extensive and diverse infrastructure, which includes water supply wells, dams and pipelines. An improvement in operation and maintenance performance is a necessary condition for the reduction of cost. Special attention will be paid by all water sector agencies such as MAW, Ministry of Municipal and Rural Affairs (MMRA) to preventive maintenance of the facilities.

In Tihama Asir, the domestic water needs, with a few notable exceptions, can be met by means of the ground water resources. In Tihama Asir the ground water is being withdrawn at close to the maximum rate. Water quality is generally good, however,

Figure 6.18: *Water reservoir in a garden and on top of houses in Jizan City*

concerning rural supplies, there are 391 communities in the Tihama Asir. All these obtain their domestic water from wells and most have sufficient quantities to meet demand. In several communities, water quality is so poor and the water must be trucked for a distance of 50 km in some cases.

The storage coefficient is the water table in the beds of gravel sandwiched between more argillaceous beds.

Water quality varies throughout the region from about 200 ppm TDS to as high 1O,000 ppm and above. In rare locations within the same aquifer field the quality can be substantially different: for instance groundwater samples taken from Wadi Itwad basin have range from 250 ppm to over 4,700 ppm. For human consumption the norm is 500 ppm but values as high as 1,500 ppm have occasionally been found to be acceptable. However, beyond this level the water can no longer be considered as potable but instead is referred to as brackish. Some tribes, hardened to desert conditions, can accept brackish water with salinities higher than 2000 ppm. Desert livestock can drink water with a salinity of about 7,500 ppm.

From an inspection of some of the various reports on water it has been possible to draw up a statement of total groundwater extraction throughout the area.

Gross extraction is defined as the total withdrawal from the ground whilst net extraction is defined as the total water consumed. The difference between these two is the quantity returned to the ground by irrigation drainage. Of the total used, 14% is consumed within cities and other population centres, while the balance of 86% goes to irrigation (Table 6.5)

In certain cases, such as water use for domestic or for agricultural irrigation, there appears to be much room for a straightforward reduction in demand without creating any serious hardships. Population will continue to increase, but *per capita* demand may be modified. In the agricultural sector, the situation is at once more promising and more complex. To some extent technology, related to irrigation equipment and to irrigation scheduling, will be able to curtail water demand.

At present, water security is being jeopardised in favour of short-term food security, which will in the short term lead to achieving neither objective. In order to provide a brief overview, the findings of the preceding sections are in Table 6.6. Specific water demands are identified in the table. From a planning point of view, there remains the option to either resource. Therefore, resources are also introduced in the modelling runs by reducing the demand uses.

Table 6.6: *Summary of Resources Potential*

Sector	Current Use 1985 (mcm/y)	Projected Use 2000 (mcm/y)	Target Use 2000 (mcm/y)	Conservation Potential 2000 (mcm/y)
Domestic/Industrial	1165	2501	1196	1305
Landscaping	3468	4745	712	4033
Agriculture	7430	21600	15120	6480
Natural Loss Reduction	--	--	--	100

The total irrigation use is split into beneficial and non-beneficial use being 50% and 36% of the total extraction respectively. The beneficial use is transpired by the area's total biomass, the non-beneficial use representing that water which drains below the root zone back into the water table (incidentally leaching the soil of any excess salts) and evaporation losses in transmission and distribution. This latter element probably amounts to 10% of the non-beneficial use.

Water distribution is only satisfactory in Abu-Arish. In the other cities, water systems are inadequate and water quality is low. This is due to losses and seepage which are relatively high, about 30-35% of total volumes produced, especially in Jizan.

6.3.5 Summary

Tihama Asir domestic water demand has led to the design and construction of networks in Jizan, Sabya, Abu-Arish and Baysh, in order to improve water quality and distribution. Connection rates are 75% of households in Jizan, Sabya, and Abu-Arish, and 50% in Baysh. Unconnected houses are supplied by standpipes or by municipal supply.

Under these conditions of insufficient production capacity and unsatisfactory distribution, *per capita* consumption has remained fairly low. It is about 0.037 m^3/capita/day for unconnected households. The daily consumption of connected households is between 0.060 m^3/day, 0.077 m^3/day, 0.109 m^3/day and 0.163 m^3/day in cities of Tihama Asir.

These figures refer, however, to volume produced at the wells since no metering of actual consumption is recorded. These figures include domestic, municipal, light industrial user seepage.

Conclusions

In general, due to Saudi Arabia's very high oil revenues and the government's plan to decrease economic dependence on the export of crude oil by diversifying resources as far as possible, more emphasis has been placed on the fields of agriculture and industry. A wide range of financial incentives, as mentioned earlier, has been offered by the government to the citizens for the purpose of developing these fields. Therefore, water demand in Saudi Arabia is increasing constantly. The extraction of more water from shallow wells should be reduced in order to alleviate the decline of the water table and the deterioration of cultivatable land. If no restrictions are placed on water use, along with the expected increase in per capita water consumption, will continue to place unreasonable demands on the capacity of the supply systems presently under construction. Improved research concerning water supplies and consumption is necessary for achieving better water policy planning in the cities.

1. Water shortage problems in Saudi Arabia result from increased urbanisation and industrialisation, and a greater *per capita* water demand, rather than a resource shortage.

2. Substantial progress has been made in satisfying the water needs of Saudi Arabia's population. The rapid increase in water consumption raises importance of the development of the water sector in most areas. This is the significant shift which has taken place in Saudi Arabia's water demand.

3. Regarding water use demand for agricultural irrigation, it has been found that farmers use surface water irrigation. In order to encourage farmers to take greater care in their use of water, the government needs to persuade farmers to make use of other irrigation systems. Such large variations in efficiency imply potential savings of water by the introduction of different kinds of water irrigation system. Such a reduction in demand would go some way towards alleviating the water supply problem in Saudi Arabian agriculture.

4. The Saudi Arabia government has implemented a number of development projects in selected parts of the country, in areas which possess rich water resources and fertile soils, such as Al-Hassa and Al-Qatif in the eastern parts of the country, and Wadi Jizan and Wadi Dammad in Tihama Asir. One of the largest schemes is an irrigation and drainage project at Al-Hassa Oasis.

5. With rapid urbanisation in Saudi Arabia, the rising demand of towns for drinking water has become increasingly difficult to meet from local sources. An associated problem is the *per capita* increase in water demand, as standards of living rise. In rural communities, the daily water requirements of an individual may be as little as 20-40 mcm, but the fashionable quarters of the larger cities *per capita* water demand probably approaches 500 mcm/d. Three government departments are responsible for the domestic and industrial supply of water, these are the MAW, MRA and CCWS. Water supply distribution networks have

been installed in many of the larger towns and cities and in the current development plan (1985-1990), new or enlarged projects are planned for Riyadh, Jeddah, Makkah and others.

6. A differential rate structure for water prices should be established to eliminate unnecessary use of water. In order to decrease water consumption, the government should reduce subsidies so that consumer prices are closer to the actual costs of water supply.

   The current water withdrawal by city wells, such as Riyadh city, is 75,000 m^3/day. The balance is made up with desalinated sea water pumped to the cities. In addition, a daily water quantity of about 450,000 m^3 is used for irrigation in Al-Hafuf. The present withdrawal quantity from both locations and in other areas is still below the rate of replenishment. Therefore, water production from aquifers, such as Wasia could be increased from 75,000 to more than 300,000 m^3/day, provided that the other production areas remain constant with their quantities for safe yield. To avoid a rapid water decline in the future, locations were chosen with regard to water quality and distance from the cities, in order to keep the water cost as low as possible.

7. To compensate farmers who use less water for irrigation and who eliminate water dissipate, a tax quota system should be established. This system could be applied by assigning a fixed allowable quantity of water for each acre. Farmers could exceed or fall below their quotas, but each farmer is assessed a tax according to the quantity used compared to his quota.

8. The three water demand uses are domestic, agricultural and industrial. Agricultural water demand rose faster, from less than 2,000 mcm/y to an estimated 7,430 mcm/y.

   The need for potable piped water will continue to grow as urban areas grow in Saudi Arabia. The government has supplied all water to industry. Municipalities receive their water free of charge. Domestic use is subsidised in the case of large users. This policy promotes the profligate use of water, which appears short-sighted given the fact that most of KSA's water sources are non-renewable and that use is going to grow with urban and industrial development.

9. The general approach of the area to meet the high growth of water demand, which is mainly due to expansion of the agricultural sector, is by increasing the water supply such as building more dams, and drawing off and piping more water from aquifers.

10. In Tihama Asir, the increased growth of major cities has led to the exploitation of more remote groundwater resources.

    Urban water demand projections for the region are based on the present rates of consumption, the present and projected total mean annual consumption by principal towns and supply area. The total is expected to rise from 8.7 mcm/y to 54.9 mcm/y, more than a 500% increase.

    Maximum use must be obtained from the wells for supplying water to towns. The current daily water production supplied to towns is about 66,000m^3 with a daily withdrawal for irrigation of about 88,700m^3. Total withdrawal exceeds the average daily recharge rate of 125,000 m^3/day by nearly 30,000m^3.

    Under such conditions, withdrawal reduction is strongly recommended to ensure safe, continuous production. The overdraft problem can be solved, and increased withdrawal for the area's supply can be achieved by prohibiting water withdrawal for farming. A continuous water supply of at least 100,000m^3/day is likely without jeopardising the ground water reserves, since the pumpage rate is below the average recharge.

    The farmers in the area should be compensated by:

    a. being provided with other farm lands in the Tihama Asir region.

    b. being allowed to draw groundwater from aquifers.

Chapter Seven

Water Balance and Budget Water Supply

7.0 Introduction

In order to assess the availability of water resources within the study area, it is clearly desirable that estimates of the mean water balance for each area catchment should be made. Whilst data on rainfall, runoff and groundwater volumes and extraction are available, the direct quantitative determination of recharge remains an intractable problem. Estimates of recharge have, therefore, been made by indirect means.

As the aquifers of the country are composed almost entirely of extensive gravel-filled wadi beds, it may seem a simple matter to measure runoff only, on the valid assumption that all runoff, less evaporated detention storage, eventually goes to recharge. Because of the peculiar runoff characteristics exhibited by most wadis, referred to above, it has not, however, been possible to determine the amount of runoff with any precision.

Utilising these data obtained at a number of sites to check various indirect methods of calculating the amount of water made available for runoff and infiltration after actual evapotranspiration loss has been accounted for, which is a modification of an expression to determine actual evapotranspiration first, provided valid results. The results of these tests are contained in Specific Report No. 2 (Hydrologic and Climatic Investigations) and notwithstanding the admittedly restricted amount of data available, good agreement is obtained between observed and calculated values of total available water.

As a further check on these estimates a comparison between rainfall input and aquifer extraction in each catchment is made. The results of the comparison, when considering the various additional factors in the hydrological sequence, are remarkable. For each catchment the average annual rainfall for the ten years was determined. This rainfall input then undergoes a complicated sequence through interception, detention, evaporation, evapotranspiration, runoff, infiltration and recharge. Despite this long sequence involving a number of variables, the relationship between rainfall input and extraction in nearly all catchments with the exception of wadis are surprisingly good. Such a relationship would imply that in most catchments, extraction is in equilibrium with recharge which, over a long period of time, would be a natural response. This relationship is, however, imprecise and particularly so since rainfall has only been determined for a period of these years. From an examination of the scanty longer rainfall records that exist, it would seem however that the average of these years represents, fortuitously, a value close to the longer term model value at annual rainfall over the country.

The emphasis on water resource development in Saudi Arabia so far has been too much on providing additional water supplies through generally costly technological solutions. However, this approach has tended to concentrate only on one side of the water equation, in increasing water supply. Nonetheless, it is argued that if any lasting solution to the problem of water shortages is to be found in the country then a more balanced approach must be adopted which will seek to reduce demand as well as increasing supply.

The balance of water equation of available water resources can be assumed by extrapolation from climatological data, and by data from populated areas, where a fair amount of water is supposed to be in use.

Of course efforts to do this might not be popular among many sections of the population of Saudi Arabia who are becoming more and more used to increasing water intensive lifestyles. However, the basic problem is that the water supplies are simply not available to meet the demand for water, many barriers exist which will restrict the ability of Saudi Arabia and the Tihama Asir to develop new water sources to the level required to meet future demand.

An attempt shall now therefore be made to some areas where water resource development strategies might become focused in order to ensure a far greater balance between water supply and demand which can become the basis for a more realistic but sound programme of social and economic development.

This deficit was estimated to be about 100 mcm in 1987. The government has concentrated its strategies and efforts on tapping groundwater and constructing desalination plants along the coasts, but there has been relatively minor attention devoted to other possible water resource development projects.

An overall plan for water management must be devised to increase the efficient use of the country's scarce water supply and to decrease the rate at which non-renewable water resources are being depleted, some of the approaches and achieving greater water sustainability in Saudi Arabia:

1. Lake dam
2. Desalination
3. Re-use of waste water
4. Groundwater aquifer.

In the following section, the principles of input-output are used to formulate water use alternatives. The purpose of the input-output is to formulate water use alternatives in Saudi Arabia. The boundary of the water resources system of the country is considered to coincide with the geographical boundaries of the country.

Two time frames have been chosen to investigate the potential of the methodology: a base year and planning to future. The data requirements are determined by the municipal use system, the agricultural use system, and the industrial use system, which are the internal components of the matrix.

Most the water will continue to be the major physical constraint to expanding Saudi economic development because of its scarcity in many regions of the country. There are no perennial streams, and despite several technical innovations, desalinated water and sewage water. The huge aquifers of fossil water have turned out to be a non-renewable resource. The internal resource deficiencies combined with the tremendous growth in population and water uses have resulted in water demands far exceeding the available supply.

The water requirement is expected to increase approximately two-fold by the year 2010. The increase in water requirement is very substantial, nevertheless, history shows that this kind of growth in water requirements is quite likely if the present water practices are not changed. The confined aquifers provide the country with about 77% of its water requirements. The alluvial aquifers supply water on the order of 9% of the total water requirements. Most of the groundwater is used in the agricultural activities. The desalted water which represents about 7% of the total water supply is utilised for municipal water. Surface water, which is about 6% of the available water supply is mainly utilised for irrigation (flood irrigation). The renovated water is in the order of only 1% of the total water supply and mainly used for recreation as well as for cooling purposes in the industrial sector.

The water resources (groundwater, surface water, and desalinated water) necessitate the extensive introduction of entry components. The exit components are conventional ones, atmosphere and seepage.

7.1 Water supply for KSA cities and towns

In recent years, considerable efforts and funds have been devoted to the search for increasing the water supply. All cities and towns in KSA are supplied by groundwater aquifers and surface water from the wadis. Water budget development does not differentiate between agricultural and those for municipal and industrial uses.

The agricultural development which the Saudi Government is pursuing at present aims at discovering groundwater resources so as to overcome the scarcity of water which has been hampering agricultural development. Some hydrological surveys have been completed and implementation of the findings of these surveys might help the country in tapping into and utilising underground water supplies which are not in current use and offer some guide lines for a more efficient utilisation of existing supplies.

It may be argued that this is a reasonable supply of water for domestic, industrial, oil field injection and agricultural irrigation water. Water supply is divided for this purpose into four kinds with a total used water supply 14,512 mcm/year. There are significant reserves of good quality water and sufficiently large areas of fertile soils in wadis. Large quantities of water are also found where the deepest fresh water well in KSA is located 700 g/m at a depth of 2.25 m.

In KSA, water supply includes rainfall, surface water, groundwater, desalinated water and sewage water. But in these there are no inland revenues and where the most populated regions frequently face water shortages and droughts, water has always been a precious commodity. The government works to meet the challenges and demands of modernisation, efficient and innovative management of the country's water resources is probably its most·important task.

This process of surface water is the crucial means whereby water is concentrated into stream flow down the normally dry water beds, which in turn can lead to aquifer recharge. This last process is particularly important for both rural and urban development in semi-arid areas and it is worth appreciating that water available for recharging is always fully intercepted.

last process is particularly important for both rural and urban development in the semi-arid areas and it is worth appreciating that water available for recharge is not always fully intercepted.

Expressed as a percentage of the total annual rainfall input, surface water quantities range across the country. Individual storms, depending upon preceding catchment conditions, can result in considerably higher surface water values.

Saudi Arabia has identified 20 principle sources of underground water of various quality; nine of these that are now being exploited have proven to be abundant sources of high quality water. The country's total reserves of this nonrenewable resource are put at round 3.5 billion cubic metres [bcm], while renewable reserves in surface and shallow aquifers are estimated at about 1.2 bcm, [see chapter 4].

7.1.1 Surface water in KSA

There are no wadis in KSA where streams or rivers flow all year round. However, a number of dams have been built or are being built to store seasonal rainfall.

In general, runoff occurs in dry valleys, but often does not reach the sea because of high pates of evaporation and infiltration into the wadis alluvia.

Many dams have been built throughout Saudi Arabia, in an effort to control water flow, recharge aquifers, and store rainwater in natural reservoirs both for human consumption and agricultural use. The MAW has built between 170 to 200 dams (chapter 3).

The average annual precipitation over the country is about 100 million cubic metres per year (mcm/y). This represents the best estimates we can presently make of flow rates. Saudi Arabia has temporary runoff which occurs whenever there is an effective storm. MAW has been studying different basins in the country, where it was found that the mean annual runoff is about 2,025 mcm of which less than 30% is diverted for agriculture, 45% is infiltrated, recharging the groundwater aquifers, and the rest is lost due to evaporation.

7.1.2 Ground water in KSA

The underlying aquifers are recharged by deep percolation from land above.

The potential with regard to climate, topography, soils and human resources offer a wide range of opportunities for agriculture, but the irregular and unpredictable occurrence of surface water is the main constraint.

Groundwater is frequently non-renewable and is likely to be the major source of supply. Aquifers are described as "confined" or "free flowing".

Groundwater in confined aquifers is stored in water-bearing formations under pressure. When a borehole encounters a water producing area water rises in the borehole to an altitude which is dependent on the pressure.If this pressure is sufficiently high, the water flows at ground surface level. Groundwater from free flowing aquifers flows to the surface under its own pressure (from artesian well). The depth of aquifers varies considerably: between 75-250 m. In most cases the depth of artesian wells does not exceed 50 m. These aquifers currently supply more than 75% of the country's water needs. Saudi Arabia's water requirement is around 9,600 mcm (see Chapter 4).

7.1.3 Desalination in KSA

The development of KSA depends to a large extent on the availability of adequate water supply. Sustained economic growth is impossible if different areas in KSA have acute water shortages, are threatened with possible exhaustion of water reserves or are faced with a steady increase in the salinity of water.

During the past, urban and industrial expansion as well as agricultural development has occurred in most cases prior to the carrying our of comprehensive water surveys. Since the magnitude of fresh water reserves in a number of areas is unknown, economic development in various sectors, as well as planned economic development projects, is endangered by the possibility of the water being exhausted or of its quality being deteriorated. The desalinated water is blended with brackish groundwater to produce drinking water for domestic use in major cities, and for agricultural irrigation. KSA has ample access to sea water as a resource along the coastline. The salinity of the Red Sea is about 500 mg/m^3 and of the Gulf about 800 mg/m^3. The development aims to increase the production of desalinated water from 40,000 m^3/day to more than 50,000 m^3/day in 1995 (see Chapter 5).

7.1.4 Waste water recycling

The utilisation of waste water in KSA has been considered by the MAW for almost three decades.

The pursuit of waste water as a source of water supply was set off by the historic developments of 1970s which led logically to enormous volumes of domestic and industrial waste water being discharged into municipal sewer systems.

Nevertheless, apart from the image problem, there remains the real risk of unknown health hazards associated with treated sewage. The reuse of domestic and industrial waste water in Saudi Arabia. This is partly die to poorly developed sewage collection systems. The General Petroleum and Minerals Organisation (Petromin), began using effluent from Riyadh for use in the refining process. The farms in Derab and Dereyah were conveyed 280,000 m^3 of reclaimed waste water. Other plants for waste water reclamation are being in the major urban centres such as Makkah and Jeddah.

Although such a flow rate appears to be rather small compared with the various water demands now in evidence, that availability of waste water near the centre of municipal and horticultural activity gives it a distinct advantage over more exotic resources.

For this source it was assumed that would gradually increase to 250 mcm in 2000 (see Chapter Five).

7.2 Water supply for the towns in Tihama Asir

In Tihama Asir water delivered to the towns, is satisfactory in view of the climatic conditions having an adverse effect.

All the towns in the area study are currently supplied only by groundwater from the alluvial aquifers and surface water in the wadis nearest to the towns. Those are supplied exclusively from Wadi Jizan, Subay, Baysh, Dammad and Itwad, by a series of wells situated between 1 to 20 km upstream from the towns.

The amounts currently taken daily from the wadis have been roughly estimated as indicated in the table below. The tables below show that, compared to water use over the past few years, the agricultural use of water is set to increase much faster than use in urban areas.

The monthly variations in the runoff coefficients for some wadis clearly demonstrate the influence of domestic use and irrigation. It will be seen that the runoff coefficient decreases considerably and in a random manner during the months of low rainfall and small floods.

Under natural, undisturbed conditions the loss components of the hydrologic cycle in the area study is very significant. Even minimal rainfall of 91.4 mn/year would deliver 50,000 mcm/y to the territory, but at the moment less than 3% of the renewable supply is being utilised.

Recharge is by infiltration of wadi flow, for estimates of this resource in Tihama Asir, and the surface water in the area after rainfall is used for urban and agricultural use. A total value of about 12,735 mcm/y is used in this area, allowing for artificial recharge to the deep aquifers.

Unfortunately, the hydrology does not support the feasibility of surface runoff breakthrough in terms of salvaging more of the natural losses. By far the largest loss factor is evaporation from the surface. Generally, the most favourable assessment of modifying the hydrologic appears to point to conducting thorough feasibility studies aimed primarily at resources. On a national scale perhaps a range of 50 to 100 mcmy represents a reasonable estimate of the potential scope for generating new natural supplies.

In recent months conservation has considerably gained in stature as a potential water resource for Tihama Asir. In certain cases, such as water use for domestic consumption and ornamental irrigation, there appears to be much room for straight forward reduction in demand without creating any serious hardships.

From an inspection of some of the various matters relating to the water survey areas they have been able to draw up a statement of total groundwater extraction throughout the Tihama Asir area. Gross extraction is defined as the total withdrawn from the ground while net extraction is defined as the total consumed. It will be noted that 14% of the total is used within the cities and other population centres while the balance of 86% goes to irrigation.

Assuming 8 plants for a 4 member family, and water use (of drinking water standard) of 0.025 m^3/day this would require 25 x 8 = 0.2 m^3/day/family. This assumption appears reasonable for flat dwellers, or anyone who is not able or willing to cultivate outdoor garden space. A villa (10 m x 10 m) surrounded by 2.5 metre strip, half of which is planted with sturdy vegetation requires 0.01 m^3/m^2 of poor quality raw water in the 2500 to 3500 ppm range.

As used here the target demand reflects a level of consumption which meets all basic biologic and hygienic needs. Such a level can be achieved by using the best available technology in each relevant water use sector. It is postulated that 0.05 m^3/capacity/day (about 70 m^3/year for a family of four) is sufficient to water more than 200 m^3 of residential target demand would be 0.252 m^3/capacity/day. It is commonly accepted by practitioners in the water sector in the area that production costs are difficult to define, primarily because producers are under no compulsion to keep track of their costs since they are expected to provide water to the municipalities without charge.

In the preceding the water was made to irrigation of public landscaped areas and tree plantings in road. Severe arid climates discourage permanent growth of most vegetative species.

The perceived need for greenery, and hence for landscaping and its irrigation is a very subjective concept, and obviously the benefit of satisfying that need has to be compared with cost. The latter involves the acquisition of landscape infrastructure, such as plants and irrigation equipment and the continuing cost of purchasing irrigation water.

The observation referred to earlier on water in Jizan and Sabya indicated that current water use for ornamental irrigation is approximately twice that allocated for residential inhouse purposes.

The scope for landscape irrigation conservation would, therefore, appear to be in the order of 0.85 m^3/capacity/day, suggesting an overall potential of about 1.100 bcm/year, maintaining a constant unit rate of 0.1 m^3/capacity/day.

From the previous it is possible to tabulate Tihama Asir area budget water balance data based upon the findings of the separate water study areas. This also identifies the nature of the date used. This presents a schematic of the indicative water balance budget for the Tihama Asir area.

7.2.1 Surface water in Tihama Asir

Because of low precipitation, stormwater drainage has often been neglected in the past. Nevertheless, rains, although infrequent, are of high intensity and thus very destructive.

The mean volume of rainfall over a given domain is measured and compared with the volume of rainfall over the climatology control area. To add more detail to the water balance over Tihama Asir, estimates of annual precipitation amount to nearly 21 bcm, and actual evaporation some 25 bcm, to within 20% of precipitation. This precipitation averages more than 500 mcm/y. The annual outflow is around 402 mcm. Every year in the area, 62% of surface water runs to the Red Sea.

7.2.2 Groundwater in Tihama Asir

In Tihama Asir water supply includes rainfall, surface water and groundwater. But in Saudi Arabia within Tihama Asir water supply also comes desalination and sewage water.

Pres, fractures and other voids in the ground provide the storage space for groundwater and the amount of water that can be stored may be assessed by observing the volume of water accepted or released from the ground for a given rise or fall in water levels by well pumping (see Chapter Four).

The total lands surveyed in the study area is 450,000 ha, of which some 35,000 ha could be irrigated. They cover 16 wadis of irregular width on both sides of the wadi course, stretching from the end of the foothills in the northeast, downstream to the saline coastal plain in the southwest. The area is of low relief, with gentle slopes from the foothills to the sea coast with a gradient varying between 0.5% in the upper parts to 0.1% in the lower parts at the coast. The following is a summary of the present farming systems in the area:

1. Total flood irrigated area of some 3.5×10^8 m^2 depending entirely on irregular floods coming down from the mountains. Farm sizes are between 2.0×10^4 m^2 and 3.0×10^5 m^2.

2. Pump irrigated farming of some 5.0×10^6 m^2 to 6.0×10^6 m^2 at present mostly along the roads near large settlements and lower parts of the wadi courses. Farm sizes are between 5.0×10^4 m^2 and 1.5×10^5 m^2.

3. Dry farming on the saline soils and in the sandy dune areas along the coastal strip. The strip is some 150 km in length by 8 km in width.

4. Dry farming in the foothills area. The strip is some 150 km long by 5-10 km wide and hilly, with varying slopes.

5. Dry farming in the plain. The strip is some 100 km in length and some 20 km in width between Wadi Baysh and the Yemen frontier. Some 75% of the area is suitable for irrigated agriculture.

7.3 Water policy in KSA

7.3.1 Internal components

a. **Municipal sector:** Municipal uses include residential (domestic), commercial, public, recreational, and industrial uses that are tied to the municipal system and losses incurred in getting water to consumers. Forecasting these requirements is normally based on the projection of establishing growth trends in population and daily per capita needs. The daily per capita use varies with population, national and individual level of income, level of education, precipitation, temperature, price of water, degree of industrialisation, and the standard of living.

The water usage amounts in Saudi Arabia do not represent the total municipal water requirements because some parts of each city are not connected to the government water network. These non- connected houses meet their water needs from local sources, which are not included in collected data. The percentage of connected houses differs from one city to another. However, the percentage of connected houses has been increasing since 1980 (MMRA). Further, the government estimates the average use of a house that is not connected to the water system to be around 75% of those houses which have the system.

b. **Agricultural sector:** The irrigated agriculture sector, which included livestock watering, is considered the principal demand sector in the country. 70% of the total water requirements in Saudi Arabia are from this sector, according to the Ministry of Planning Annual Report 1980. These requirements are a function of several natural variables, such as precipitation, runoff, temperature, evaporation and soil condition, and many socio-economic and technological factors like population, income, method of irrigation, and effectiveness of machinery.

c. **Industrial Sector:** The industrial water that is not supplied by municipalities, but by private wells. This is because industrial water taken from the public system has already been included in the urban water requirements. This was done because the industrial sector in Saudi Arabia is relatively small, although it is expanding rapidly. Industrial water use may be classified into water for: cooling (largest water use for the industrial sector), boilers, processing, and miscellaneous uses (MAW).

7.3.2 The components

a. **Atmosphere:** The component includes water lost by evapotranspiration and consumptive uses (see Chapter 2 - Climate).

b. **Recharge:** Water input to this exit component is surface water lost by infiltration and seepage (see Chapter 3 and 4).

The availability of a reliable water supply of good quality and quantity is a necessity for the social and economic development in any country. The development of the water resources is determined by the pattern of demand and supply forces. On the one hand, population expansion, increased urbanisation, industrialisation and agricultural development determine the quantity and quality of water demand. On the other hand, the availability, quality and cost of water influence both where this growth will occur and the nature of economic development. Water policy is, therefore, an integral part of a comprehensive developing planning process.

In addition to the MAW, which is the agency primarily responsible for implementing the water policy, three other institutions are also involved in planning, management, development, production and distribution of water supplies.

1. The Saline Water Conversion Corporation (SWCC) which is mainly responsible for the construction and management of water desalination plants.

2. The Ministry of Municipal and Rural Affairs (MMRA). This ministry takes charge of the construction of all municipal water distribution networks and associated storage and maintenance facilities as well as sewage collection systems and treatment plants at large and medium-sized population centres.

3. The Al-Hasa Irrigation and Drainage Authority (HIDA), an autonomous body, is in charge of the Al-Hasa project, the country's largest irrigation and drainage scheme.

The great emphasis to develop and maintain an adequate water supply can be grasped from the large volume of capital investment undertaken by the above government agencies on water development. For example, about £9.73 billion was allocated for water resources programmes between 1980-1985 compared with about £6.25 billion spent for the same purpose between 1975-1980. The concern about water is continuing, therefore, nearly £5.88 billion was allocated for the Fourth Plan 1985-1990 to meet future water needs. This is becoming particularly critical as the following developments are anticipated:

1. Urban industrial use of water which stood at 502 m^3 annually is expected to grow rapidly to a projected 2.279 million cu.m annually in 1999-2000, as a result of the expanding water demand. Tihama Asir use of water will be 40,500 cu.m. 1999-2000.

2. Agricultural use of water for irrigation is also expected to grow from 1,832 million cu.m annually in 1979-1980 to 3,220 million cu.m annually in 1999-2000 as the sector continues its growth. Tihama Asir area's agricultural use of water will be 50,500 cu.m in 1999-2000.

Attention now turns to agricultural and urban water demand.

3. Since 1965 an extensive study of groundwater investigation has been underway. The country was subdivided into eight regions, largely on the basis of hydrogeological information. Consultant firms were selected to undertake the projects. As a result of these surveys, various rich water aquifers have been found. By 1983 twenty main aquifers had been established, nine of which were being exploited (see chapters 2 and 4). The main aquifers supply over 70 per cent of the country's water needs.

4. A National Water Plan for the rational use and reuse of the water resources available to the Kingdom has been prepared. The Plan calls for a comprehensive survey of water resources, assessment of water requirements for different purposes, formation of a comprehensive water policy and drafting of rules and regulations for its implementation.

5. Because of the inefficiency in water use by farmers and urban users the future emphasis, as indicated by the Fourth Plan 1985-1990, will be on the rational utilisation of this scarce resource.

Huge amounts of oil money have been invested to assure an adequate supply of water from these sources. As a result of this investment, substantial progress has been made, bringing increased water for the different consumption uses. By 1990, detailed hydrological studies regarding groundwater sources were completed and about 200 dams constructed. Furthermore, 503 million cm of desalinated seawater and about 200 million cm of chemically treated sewage water were also available.

7.4 Water Policy in Tihama Asir

The water policy lays special emphasis on the rational utilisation of scarce water resources. As future water supply will come largely from finite non-renewable reserves the main focus of the policy will be the introduction of conservation measures, strict regional water management, the establishment of priorities in water use, the introduction of tariff systems and closer coordination of agriculture and water development plans. Such policy measures will be adopted in order to achieve these objectives as follows:

1. Coordination of the development and utilisation of all water resources.

2. Maintenance of reliable data base on water levels, rainfall infiltration and evaporation based on the hydrological and hydrogeological aspects.

3. The establishment of administrative units for the enforcement of laws, regulations and water rights in order to establish priorities for water use.
4. Monitoring the consumption of all water users and the quality of water used, through the installation of water meters and the preparation of a progressive tariff system in all sectors of water.
5. Restriction of pumping rates in Tihama Asir experiencing serious depletion of ground water resources and deterioration in water quality, to levels which will sustain future water supplies and the definition of short, medium and long term pumping rates for all aquifers or parts of aquifers.

The water balance has considered the different probabilities of surface inflow corresponding to 80%, 50%, 20% and 10% or to the return periods of 1.25, 2, 5 and 10 years respectively. These probabilities are for the values of the surface inflows to be equalled or exceeded.

Despite the great scarcity of water resources, water is efficiently used. The annual extraction has greatly exceeded replenishment. Water policy in KSA including Tihama Asir, therefore, aims at achieving both proper balance and optimum use. Achieving water balance is necessary to prevent or reduce water salinity and sustain the level of ground water. The government provided irrigation water for all practical purposes. It bears the cost of digging wells and fuel cost. This practice has resulted in excessive and uneconomic use of water, which in turn increases the salinity of both land and water.

7.5 Water budget

Given that there is little margin for developing additional supplies, the tasks of analysis are to understand the water system and ferret out alternative supply-demand solutions. The existing water system can be depicted in a water balance table for the base year, for was used and water supply in it.

It is obvious that the local climate is significant to the water budget in terms of surface water and groundwater, affecting storage and surface inflow and outflow; the production and use of desalinated water and waste water; and the use of, and demand for, water for domestic, industrial and irrigation purposes.

As a result, using the technique of the climatic water budget, the impact of the region's climate on the water gains and losses can be determined: "*A water budget is an account over some period of time of all moisture gains, losses and storages for a particular place or area*" (Mather, 1978, p.3).

Most of the water comes from conventional sources, rainfall, ground, surface water, desalinated and sewage water. Sewage water is treated for agricultural use. When rain falls on the ground, it is either absorbed or runs to lower areas.

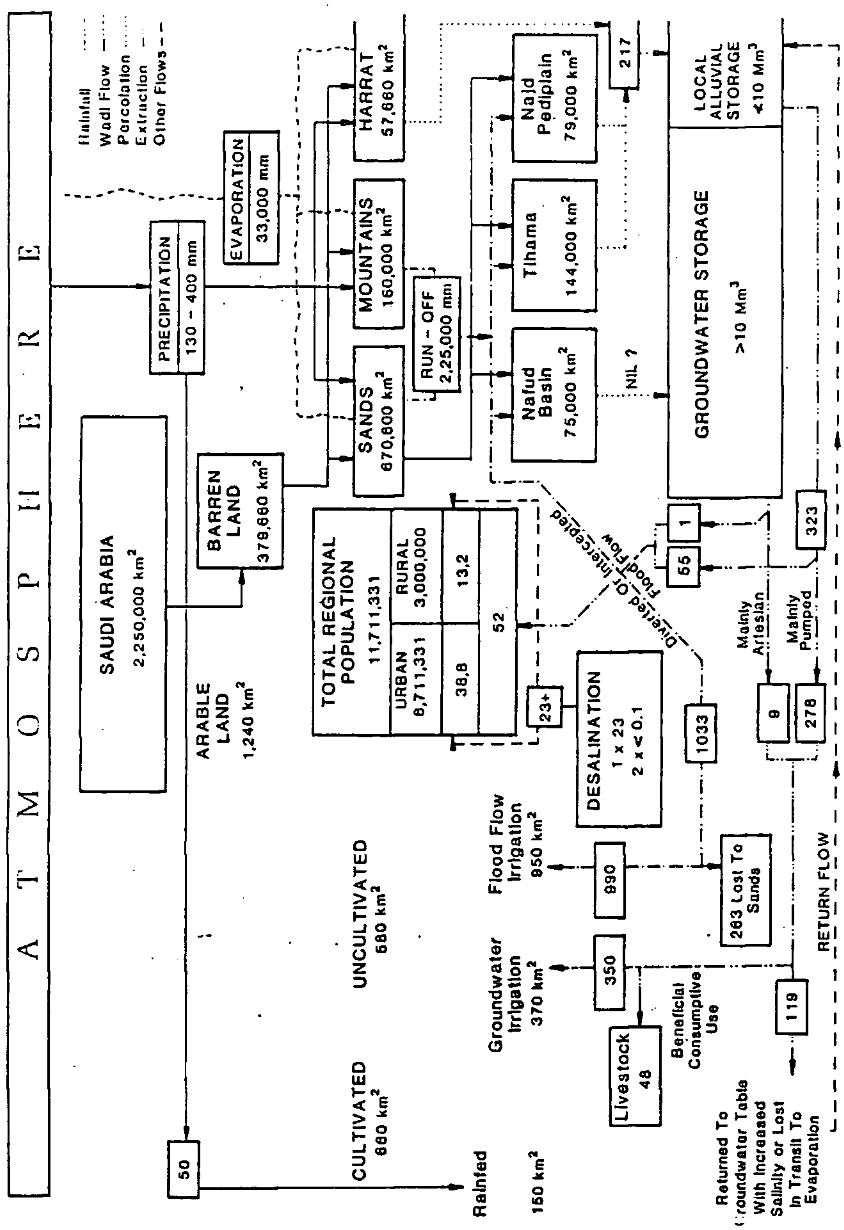
Chapters 3, 4, 5 and 6 have considered the hydrology of the water resources regarding quantity, quality, annual and seasonal flows, and wadis control systems. This chapter attempts to take account of the flow rate of water in all possible locations. It is necessary to focus on a region and determine how the quantity of water in the region can be changed. The purpose of the water budget evaluation is to identify if there is enough available groundwater and surface water to satisfy the present and prospective water requirements, in Saudi Arabia, and in Tihama Asir. The requirements for surface water in Tihama Asir, and the consequential water losses, are compared with the available water resources for each wadi by means of water budget calculations. The water supply for Tihama Asir towns is viewed in the context of groundwater resources. Finally, an integrated water budget, including the desalination and waste water supply, has been determined, considering the effects for the future management of water planned for Saudi Arabia and Tihama Asir.

Figure 7.1 attempts to summarise the regional land and water resources in Saudi Arabia, indicating the important division between arable and barren land. Approximate areas for the various subdivisions of the total are also quoted. The importance of the diagram is that is indicates the vital inter-relationship between the large expanses of land and the limited resources of water. It will be noted that the irrigation of arable land relies almost totally upon catchments located in areas of barren land, the sole exception being the rain-fed areas on the escarpment. The influence of population upon the total water resources is also indicated as is the need to draw up desalinated water from the Red Sea. Water is a subject of vital importance to the future development of the regions. However, due to the geology and climate, water is neither freely available nor easily stored. There are, nonetheless, some areas (such as Makkah, Riyadh, Jeddah, Dammam, Medina, and Taif sub-regions) where renewable groundwater stocks and associated catchment areas are extensive enough to support sizable populations with a modest average per capita consumption, a few hundred thousand people with about 516 m^3 per person per day. Each internal component is both an origin and a destination. External components appear only as columns, depending on whether they are entries. The matrix cell shows the volume of water transferred between the various origins and destinations. Amount can be given in any unit desired and can cover any convenient time period.

Once the concept of water balance is accepted it is easy to appreciate that city growth (and on a smaller scale, town or village growth) is a function of the local topography (catchment area, etc.), geology (availability of storage), climate (rainfall and evaporation), and the average standard of living of the population (per capita consumption).

Water is being used in the main cities at a rate which exceeds the natural rate of replenishment in the average year. This situation is made graver by administrative

Figure 7.1



A T M O S P H E R E
Rainfall
Wadi Flow
Percolation
Extraction
Other Flows
SAUDI ARABIA
2,250,000 km²
PRECIPITATION
130 - 400 mm
EVAPORATION
33,000 mm
BARREN LAND
379,660 km²
ARABLE LAND
1,240 km²
SANDS
670,600 km²
MOUNTAINS
160,000 km²
HARRAT
57,660 km²
RUN - OFF
2,25,000 mm
Nafud Basin
75,000 km²
Tihama
144,000 km²
Najd Pediplain
79,000 km²
217
NIL ?
GROUNDWATER STORAGE
>10 Mm³
LOCAL ALLUVIAL STORAGE
<10 Mm³
TOTAL REGIONAL POPULATION
11,711,331
URBAN
8,711,331
RURAL
3,000,000
38,8
13,2
52
23+
DESALINATION
1 x 23
2 x < 0.1
Diverted Or Intercepted Flood Flow
1
55
323
Mainly Artesian
Mainly Pumped
9
278
1033
50
CULTIVATED
660 km²
UNCULTIVATED
580 km²
Rainfed
150 km²
Groundwater Irrigation
370 km²
Flood Flow Irrigation
950 km²
350
990
263 Lost To Sands
Livestock
48
Beneficial Consumptive Use
119
Returned To Groundwater Table With Increased Salinity or Lost In Transit To Evaporation
RETURN FLOW

overlap and duplication and by private interest considerations which are generally regarded elsewhere as being inappropriate to so basic a public service as water supply. An adequate supply of fresh water is essential to a modern state, but if through natural and physical causes it is difficult to guarantee this then a water policy needs to be developed which will fully protect available resources and ensure the equitable distribution of the available supply among consumers.

In Saudi Arabia over 99% (2,250,000 km^2) of the land surface is best described as currently barren (379,660 km^2). Less than 1% (1,240 km^2) is arable. The barren areas (sands, mountains and harrat) serve as the catchments (Nafud, Tihama and Najd) for the limited water movement (runoff 225,000 mcm) within the region which is in due course used on the arable land. Reserves of this nonrenewable resource are put at round 3,500 mcm, whilst renewable reserves in surface and shallow aquifers are estimated at about 1,200 mcm (See Chapter Two). This is the best estimate which can presently be made of flow rates (mcm/y). The greatest degree of error lies within the flood flow. The influence of the urban and rural populations is shown in the central box. The role of desalination as a source of additional water is also illustrated. Annual runoff is put at around 225,000 mcm, and annual groundwater recharge is no more than 10 mcm. Desalination currently produces annually more than 500 mcm. The uses made of the output include urban domestic, industrial and leisure uses, and agricultural uses, including arable irrigation, and livestock (as in Figure 7.1).

7.5.1 Water budget in KSA

The water use for agriculture or landscape irrigation has not been identified separately in most relevant publications. It was quantified here as about 25% of published municipal use. The projection for desalination was based on a summation of all existing and planned desalination plants. The demands or uses were fixed, of the resources conservation and importation were taken to be non-existent and the other minor resources were used to the maximum of their availability. The deep groundwater is used as the swing-producer, it supplies all the water necessary for various uses, and not already met by other resources.

The balance is based on the following: utilisation of shallow groundwater, surface water, desalination, and wastewater to the fullest extent the existing facilities allow; satisfy all demands without over-producing; and produce fossil groundwater as needed to satisfy the demands.

Saudi Arabia receives water from rainfall, aquifers and wadi flows (the flow of streams, deep seepage of groundwater aquifers, and from dams, lakes, desalination plants and sewage water). The proportions of each of these sources can be controlled by the construction of dams, reservoirs, irrigation canals, pipe networks and other methods. The present estimates of average budget annual water resources include the dam reservoirs, and wadi irrigation works.

Overall water demand will increase as the population grows and as higher percentages of dwellings are connected to municipal systems.

The large cities, such as Riyadh, Jeddah and Dammam, will have the highest growth. The water use of these cities is discussed. Because of the tremendous population increase in Makkah during the Hajj, the water supply of Makkah is also considered.

The demand for groundwater is about 402 mcm, and recharge is about 85,350 mcm. Regarding dwellings, about 35% of the KSA population is connected to a municipal water system. During the decade 1990-2000, the dwelling units of an estimated 90% of the population will be connected to a municipal system.

The actual amount of water currently taken annually from the runoff and groundwater sources of supply have been roughly estimated, and presented. The same surface also contains demand. The following approximate figures were obtained from that source:

Usage	Water volume (mcm)
Cities and town supplies	1,102
Industrial complexes	110
Oil field injection	3,600
Agricultural irrigation	9,700

The urban water budget forecast is based on the present rates of consumption. The agricultural and urban sectors compete for budget water resources in that the cities' demand is less than agricultural irrigation and oil injection that a future for agriculture, and the oil use for development of heavy industrial, but the lowest used water is industrial, all supplies for natural water.

Annual rainfall is between 50 and 130 mm, and annual evaporation around 3,000 mm each year. Annual surface water in KSA is around 2,025 mcm. Daily production from desalination plants is 57,564 mcm. The annual outflow of groundwater and surface water is around 1264 mcm. The annual of the logistic is around 1520 mcm. Dam lake storage is 217,675 mcm. Sewage use for irrigation is around 397 mcm annually for input and output.

Rainfall alone in Saudi Arabia is insufficient to meet domestic needs. Rainfall variation between years is high, and when rain occurs it is highly localised. Lakes, which sometimes form during short, violent storms, are able to satisfy demand for surface water. The annual surface demand from dam reservoir storage is about 217,675 mcm for drinking water, and 2,807,325 mcm reaches the sea by means of underground aquifers, as shown in Figure 7.2, which represents projected water uses over 25 years planning, which is largely based on revision of data taken from the Fourth Development Plan, and the revised values projected towards 2000. The latter curve is the one used as a basis for the scenario analysis. Four points are worth noting:

1. Water use for horticultural purposes, or landscape irrigation, has not been identified separately in most relevant publications. It is quantified here as about 52% of municipal use, in line with experience in Saudi Arabia.

2. Conservation is rather hypothetical in the absence of any serious effort in the direction the resource may be eliminated.

3. The minor resources have not been quantified in detail, technological refinements may alter their absolute importance, but they are unlikely to have a major effect on any future water balance in Saudi Arabia.

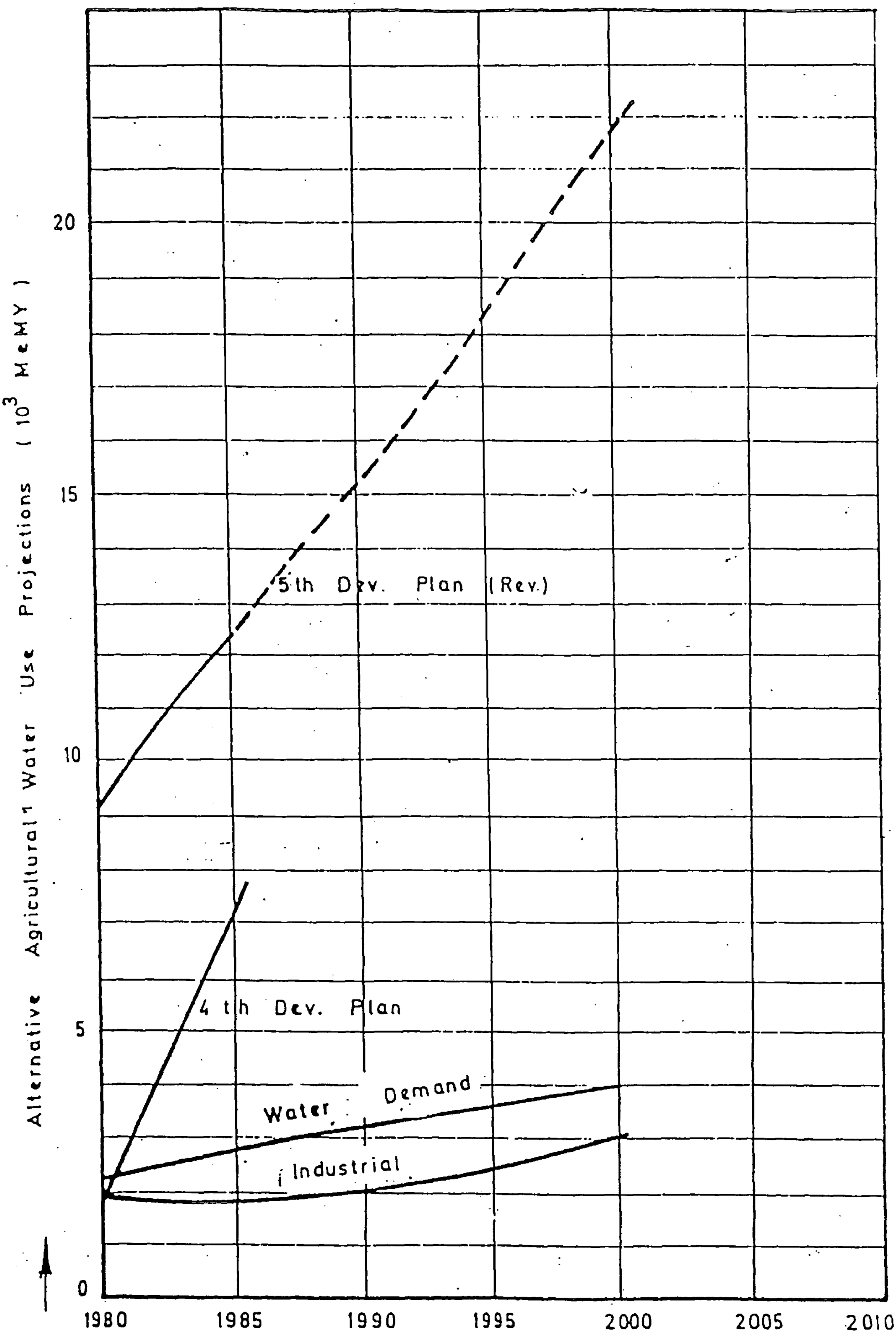
4. The projection for desalinated water was based on a summation of all existing and planned desalination plants, which appeared to be a little higher than the value mentioned in the 4th Development Plan (1985-1990). The demands or uses were fixed, of the resources conservation and importation were taken to be non- existent and the other minor resources were used to the maximum of their availability. Utilise shallow groundwater, surface water, desalinated water, and waste water to the fullest extent the existing facilities allow. Satisfy all demands (uses) without over-producing. Produce fossil desalination as needed to satisfy the demands.

The total number of hectares associated with those statistics agreed reasonably well with those shown in the figure, but there have been significant shifts in calculation at 6,430 mcm/y, and the revised values projected towards 2000 are also shown in Figure 7.2.

The development of supply and uses has impacted on the Kingdom's water resources, the rapid expansion of the water budget. However, intensive agricultural production, and the agricultural situation underlines the imbalance in its extreme form between the growth in water demand and supply. This is in stark contrast to the success of the agricultural sector. Agricultural irrigation has traditionally been the major water use

Figure 7.2,

Agricultural, irrigation and Domestic Water Use



sector in the region, usually in the range of 80-90%. It is interesting to compare projections for the Kingdom in the 3rd Development Plan (1980-1985) with the true figures published in the 4th Development Plan (1985-1990). The investigator had the opportunity to review agricultural statistics on irrigated crop lands. The total number of hectares of those statistics agreed reasonably well with those shown in the figure, but there had been significant shifts into crops such as fodder.

7.5.2 Water budget in Tihama Asir

These three methods are used to balance supply and demand between urban and agricultural uses, and between resource areas. Once water has been allocated to agriculture, it should at no time be withdrawn for urban use. This is to protect agricultural investment. The urban supply from underground aquifers in areas should be maintained in the long terms at its level. A safety margin should, however, be kept to account for discontinuities in the development of new resources such as desalination.

Three methods have been devised to establish possible ways of budgeting supply and demand between urban and agricultural uses, and between resource areas. It relies on the following assumptions:

- Once water has been allocated to agriculture it should at no time be withdrawn for urban use; this is to protect agricultural investment.
- Desalination should not be introduced before the year 1995; it should then take up all additional urban demand, thus leaving constant resources to agriculture.
- The urban supply from underground aquifer in Jizan, Sabya, Abu-Arish area should be maintained in the long term at level. A safety margin should, however, be kept to account for discontinuities in the development of new resources such as desalination.

The surplus surface water that may occur every few or several years according to the certain probability can either be used for one or more space urban and irrigation for districts, or it can be used to recharge the aquifer through the wadi bed.

The budget (balance) of water between agriculture and cities. Groundwaters have been assumed constant in areas demanding 402 mcm for urban and agricultural use, for the growth of potable water demand in urban. The amount of water available for agriculture is about 18.7 mcm.

Monthly evaporation from open and coastal water between latitudes 22°N and 22°N is estimated. If only potential precipitable water was to fall over Tihama Asir, some 32 bcm will be measured than water recycling over Tihama will be more than 70% efficient, but if east-west and north-south transport are brought into the picture, then some 3,000 mcm are flowing over Tihama and, of course, water actually falls over Tihama is less than 1% and it would seem that there is room for more efficient rain catch over the area should the appropriate technology to do so is made available. In Tihama Asir the input is entirely in the form of rainfall. This precipitation averages more than 500 mm each year. The maximum annual discharge of wadis surface water is around 1,755 mcm. The maximum annual of wadis is around 538 mcm. The water storage of the wadis is around 65,350 mcm. When see the maximum annual over the flow out around 136 mcm, then the safe the storage in Tihama Asir.

Based on the above presentation and taking into consideration the conjunctive use of both groundwater and surface water, the water balance of Tihama Asir has been calculated for satisfying the urban and irrigation use. The water balance has also considered the different probabilities of surface inflow corresponding to 80%, 50%, 20% and 10% respectively. These probabilities are for the values of the surface inflows to be equalled or exceeded.

7.6 Water management in KSA

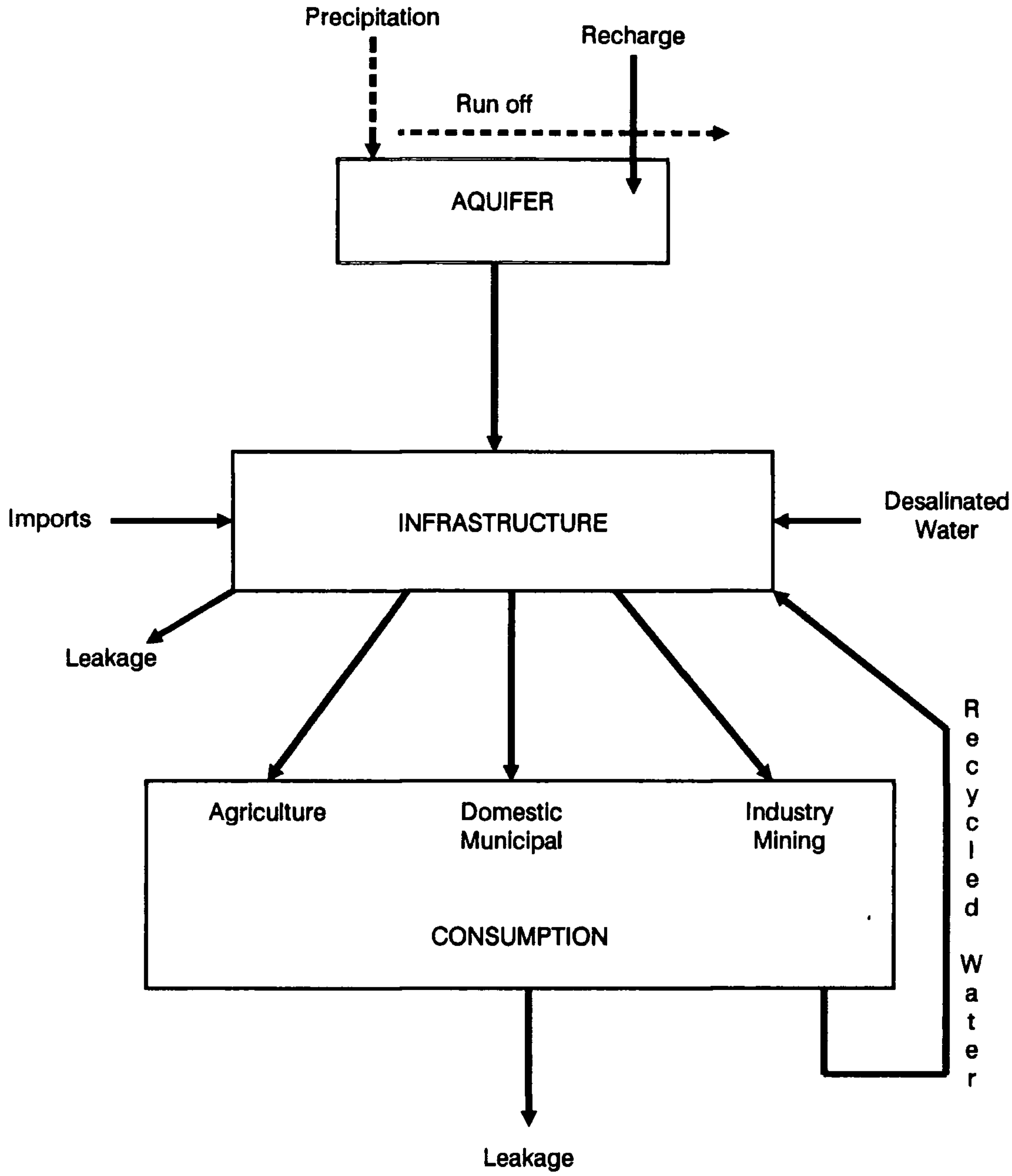
The development of water resources in Saudi Arabia is the responsibility of the MAW. The development and proper management of water resources must be controlled. Underlying all discussions of implementation is the larger concept of social change (alteration in the social system) and the associated parts of a process which include such concepts as diffusion of the technology of use and expected resistance to change. There is a great need for proper institution, the existence of organisations that would effectively maximise allocation and use of proposed water resource systems.

Water management includes the preparation and enforcement of regional master plans based on the water. Its primary aim will be the rationalisation of water use. Major elements of the water management include preparation of regional master plans for the water sector, regular assessment of water and agricultural policies, monitoring consumption in all sectors of water use, defining maximum pumping rates for aquifers, and definition, introduction of technical standards for water works and water quality and groundwater quality, and depletion of resources to the detriment of future generations.

Increased demand for water in Saudi Arabia has been met largely by the generation of more desalinated water supplies, and by acceleration of withdrawals from non-renewable groundwater storage.

Water is used for domestic consumption, drinking, washing and cooking, for industry and for agriculture. Domestic supply and industrial water demand are rapidly increasing in most countries, but by far the largest water user is agriculture. Much of the moisture used by agriculture is provided directly by precipitation, and is therefore used before it becomes part of the streamflow, supporting rainfed crops directly.

Figure 7.3: The hydrological system and water management



Source: Clive Agnew and Ewan Anderson, *Water Resources in the Arid Realm*, 1992

The water resources manager must be capable of assessing, exploiting and allocating supplies. It is also necessary to maintain the quality and quantity of supplies. Having developed a water supply it must be delivered to domestic agriculture.

Frequently more than one use is made of water: it may be needed for domestic supply, for irrigation, for hydroelectricity generation, for industrial, and sewage water. These different demands on the resource are not always compatible, if one user alters the quality of water supplies or restricts flow it may well affect another user. One of the tasks of the water resources manager is to try and ensure that various uses are compatible, and if not, to weigh up the costs and benefits and decide how to restrict use. When that is the case, the water resources manager faces much more of a challenge, and is more likely to have to negotiate between users.

In KSA, the total surface water, groundwater and artificial supplies are as follows:

1. Surface water 2025 mcm/year
2. Groundwater 1520 mcm/year
3. Lakes and dam reservoirs 217,675 mcm/year
4. Sewage water 397 mcm/year
5. Desalination plants 9000 mcm/year

This shows that the total available is 3,761,675 mcm/year and the artificial sources amount to 90,397 mcm/day. In KSA, annual rainfall does not exceed 102 mm/year. Therefore shortage of water not only hinders the expansion in agriculture but industrial development as well (see Figure 7.2), that is input water for surface demand balance water respectively, store dams and lakes about 242,675 mcm/y, and output balances are found some less water in KSA for domestic and agricultural use.

The water status of the country in the confined aquifer provides about 77% of its water requirements. Most of the groundwater is used in agricultural activities. The desalinated water which represents about 7% of the total water supply is utilised and surface water, which is about 6% of the water supply is mainly for irrigation.

Regarding water demand and the contribution of the different water sources until the year 2010, dependence on the non-renewable groundwater is growing with time, and withdrawals from confined aquifers are expected to increase from 7,300 mcm to 16,800 mcm.

Newly developed water management techniques will increase per capita available consumption. With the urban development of the country, the MAW is seeking groundwater aquifers. To mitigate this anticipated problem, a dam was constructed in the agricultural area, and flood control for recharge water.

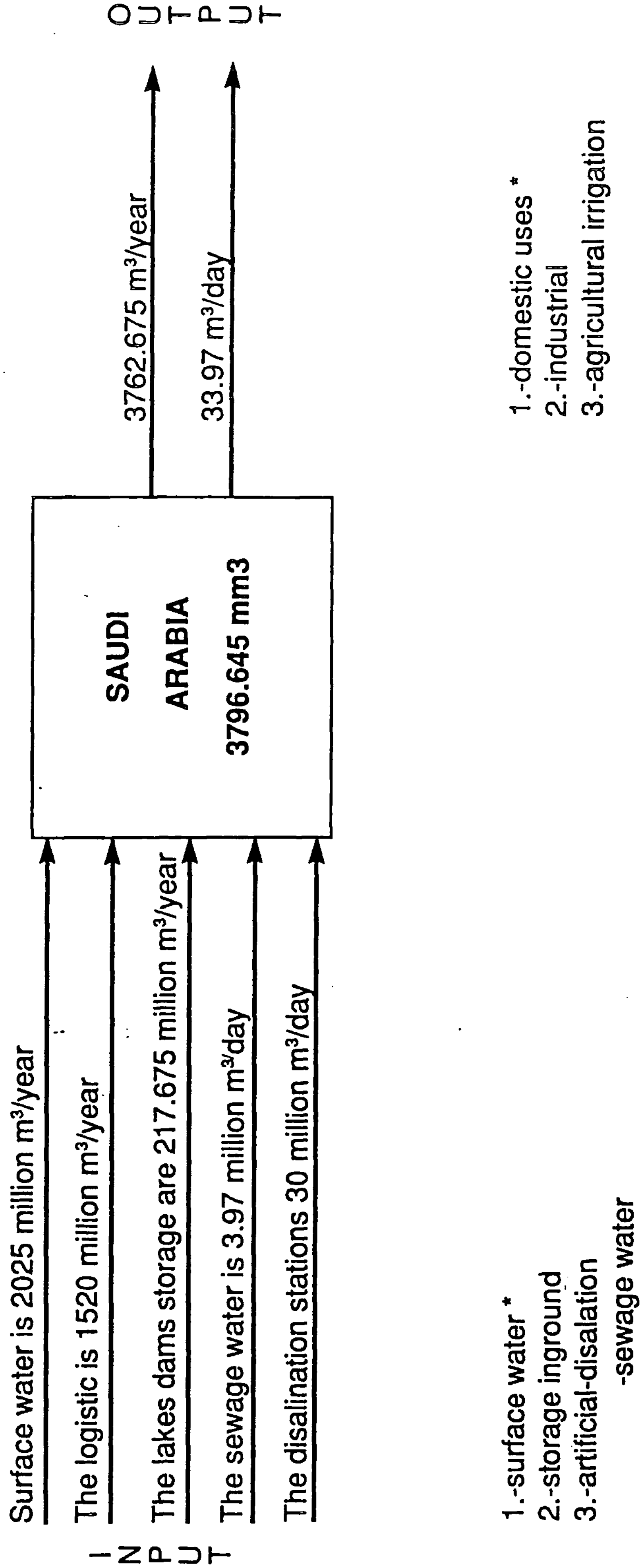
To meet the ever rising demand for water in general and for domestic and agriculture in particular, it is essential that a concerted effort be made to increase the supply of water available to uses, as shown in Figure 7.4.

7.7 Water management in Tihama Asir

There has been an increase in the number of people involved with water resources management in developing areas. The water resources management operates at the levels of national, regional watershed, wadi basin, domestic water user demand for urban, industrial and agricultural irrigation and the industrial water user.

The most important aspects of water resources management are the development and allocation of supplies. Management of water resources for agriculture may involve developing and maintaining more than one water source. Some water sources may be affected by land use more than another, some may be available to others.

Figure 7.4: *Water balance in Saudi Arabia*



The flow pattern of a wadi, the level to which water rises, the level to which it falls, whether the flows are erratic or moderated, the quality of the flow, and groundwater recharge can be modified, regulated or controlled by watershed management. Planting suitably, carefully controlling village methods, building dams on streams and constructing terraces or other soil conservation techniques can all help watershed management.

Dams often supply a reliable source of irrigation water and regulate floods. Without adequate watershed management, reservoirs are likely to become silted and land use in the catchment area will deteriorate. More water management could take place before the stream flow phase of the hydrological cycle. With modern developments in earth resources, monitoring techniques become easier for developing countries.

To be successful, water resources management must be aware of the linkages between land use, stream flow and groundwater storage. In spite of advances, there is still far from adequate understanding of tropical ecosystems, their productivity, resilience to change and the subtle, close relationships between environment and man.

The water supply from the well field located 20 km east of Jizan City depends on the groundwater, the potential of which rises with the use.

High amongst production and conservation objectives is the establishment of a unique regional water management authority. This authority should include staff from the MAW which is in charge of the implementation of the main water resources development projects from the municipal water department, and from the SWCC. The water authority would monitor all water uses and fluctuations in water resources, design long term development plans and projects. Should the provision of an adequate level of network operation and maintenance by municipal water and sewage departments be problematic, the regional authority could assume the management of the individual water and sewage department, supplying expertise from a central operation and maintenance base.

More than 75% of the arable land in Tihama Asir depends on rain feed. Irrigation water is quite limited. Because of this, access to water in the coastal area is the best prospect for expanded food production in the region. In the Asir mountains, the elevation is about 2,750 m and precipitation is fairly abundant. Thus, permitting the practice of rainfed agriculture using terracing techniques. The coastal areas have natural springs and shallow water tables along the wadis which offers Tihama's best prospect for agricultural development.

The total supplies of water are:

1. Surface water 1755 mcm/year
2. Groundwater 66,350 mcm/year.

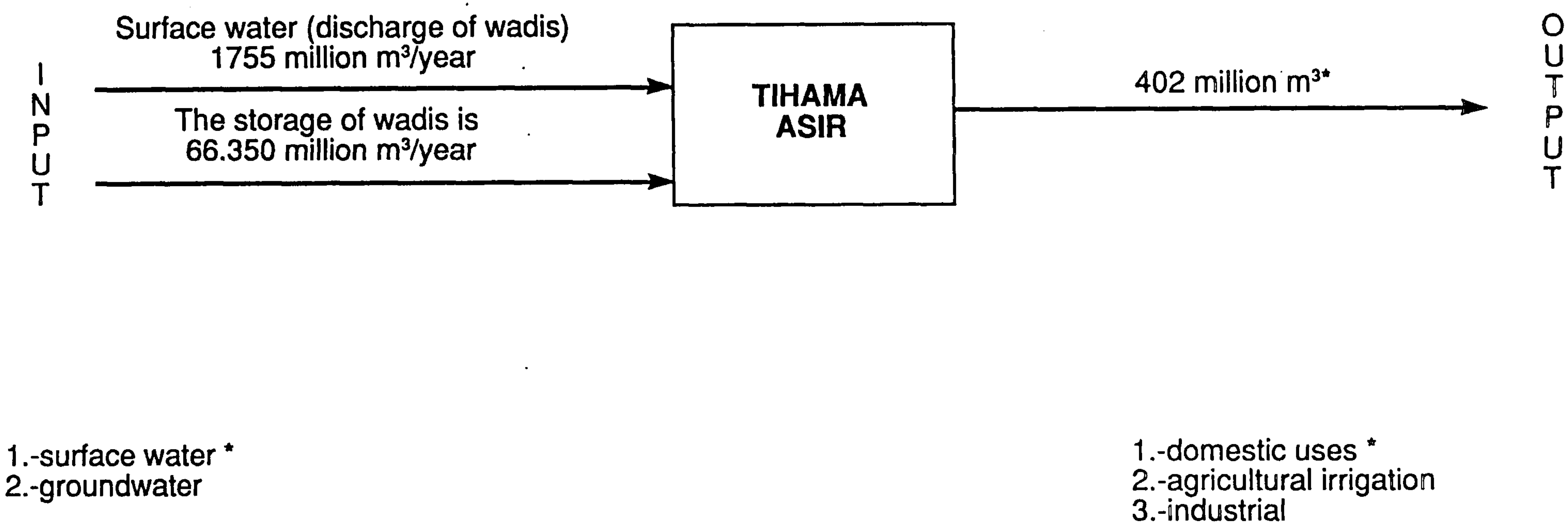
The domestic agricultural irrigation and industrial uses are 402 mcm/year (see Figure 7.5).

In the management of water, it is usual to attempt to establish a balance between income (resources) and expenditure (supply). In the situation of a favourable imbalance, the excess income may be saved or invested (recharged) and in times of shortage, resources are withdrawn from savings (groundwater). The demand is relatively fixed, and at all times adequate resources need to be mobilised to satisfy the perceived demand.

Consequently, demand management and conservation have recently been receiving more attention.

A narrow definition of conservation would probably focus on the implication of using less; a broad description might stress optimal use of water, thus not only requiring a

Figure 7.5: *Water balance in Tihama Asir*



reduction in consumption to eliminate waste and misuse, but also obtaining a more perfect match in terms of quality between supply and demand. Perhaps the best criterion is to evaluate the merit and the potential of any conservation on the quality and quantity of water.

Traditionally, the main sources of water for the inhabitants of Tihama Asir has been the hand-dug wells in local wadis such as Wadi Baysh and Wadi Sabya. With urban growth additional sources for Tihama are groundwater aquifers and surface water. Since the water supply at these sources was dependent upon precipitation, significant seasonal fluctuations occurred (see chapter 2, climate).

As the area expanded and modernised, the demand for water also increased. Water normally used for irrigation is often diverted from agricultural fields to urban consumers. A dam is to be constructed to detain run off water, particularly during flash flood events. As water is extracted from wells downstream from the dam site, the subsurface deposits are infiltrated and recharged.

Demand management in the Tihama Asir is a fairly recent concept, even though the development, at present, has as one of its objectives, to conserve and develop the present known water resources efficiently.

In each internal component is both an origin and a destination, external components appear only as rows, depending on whether they are entries or exits. The matrix cell shows the volume of water transferred between the various origins and destinations. This principle holds that total water input must equal the total water output, as shown in Figures 7.4 and 7.5, which show differences in the balance between Saudi Arabia and Tihama Asir: Saudi Arabia has a larger urban agricultural water more than that of Tihama Asir, as well as industrial development; on the other hand, the natural water resources in Tihama Asir are better than those of Saudi Arabia.

Tihama Asir differs from other KSA urban areas in annual rainfall, which is about 305 mm/year. The population was estimated to be between 600,000 to 1,155,000. There is enough water from surface and ground sources. Water slows urban growth, particularly as many people have started to keep gardens and farms: thus the need to control water is essential.

Water demand is the essential factor which plays a critical role in the effective management and development of KSA's water resources.

7.8 Water's future in KSA

Most authorities agree that water will continue to be the major physical constraint to expanding Saudi economic development because of its scarcity in many regions of the country. There are no perennial streams, and, despite several technical innovations, desalinated water is still very expensive. The huge aquifers of fossil water, the long run potential of groundwater must be considered limited. The internal resource deficiencies combined with the tremendous growth in population and water uses have resulted in water demands far exceeding the available supply. The only solution is to "create new" additional water through water resource.

The task is to use the structure of the 1980 table to transfer water from various sources of supply to satisfy the demand level imposed for each component (municipal, industrial and agricultural). To have a supply demand "Solution", the water balance constraint equations must be satisfied. In this manner, the analyst can preserve a "feel" for the solution being developed and can incorporate value judgments based upon personal knowledge. The solution was ascertained using future supply/demand conditions for the year 2000 and 2010, and non-quantifiable boundary conditions were incorporated by judgment.

Urban water demand will increase as the cities grow. Although the Development Plans 1990-1995 suggest a need for caution, and a tempering of the "self-sufficiency drive" with the acknowledgement of the limitations of the fossil groundwaters, recent press notices seem to indicate an intention to continue expansion.

The parameters of most interest are the projected growth patterns of domestic/industrial and agricultural demand, and the consequences in terms of groundwater boring and water cost yielded an estimate of this time span of 17 years, and on that basis, assuming a discount rate of 10% and an instantaneous cost increase in the year 2002 of SR 10/m^3 (about \$2.5/m^3), penalties were calculated and added to the unit costs of producing fossil groundwater.

In order to quantify the present cost of groundwater boring it is convenient to think in terms of a penalty to be paid by today's society in recognition of its preference to utilise aquifer water. Such a penalty can be defined as the present value of the extra cost to be incurred in the future in order to produce a unit volume of water (at a level of, for instance, SR 10/m^3 about \$2.5/m^3) in the absence of fossil groundwater which could have been produced at SR 2/m^3 (about 0.75 \$/m^3).

In order to complete such a calculation it is necessary to have a rough idea of the time span between today and the time of an exhaustion of the reserves. Over the past period there has been growth in most segments of the economy area an exceptional expansion in agriculture. Much of the raw water produced in the Kingdom is not directly usable and requires demineralisation, or desalination. The investigators attempted to determine realistic estimates of the costs involved, but those efforts were less successful, in part because power is supplied without charge or at a subsidised rate, and in part because many clients (municipalities, ministries, governmental establishments, etc.) do not reimburse the product. Therefore, there is no incentive on the part of that product to monitor income, or expenditure, and hence real treatment costs. The investigators found that such costs were estimated to be in the range of 1.5 SR/m^3 to 4 SR/m^3 [about 0.5 $1/$m^3$ to 1.01 $/$m^3$] for converting groundwater into drinking water, or 10 SR/m^3 to 45 SR/m^3 [about 2.5 $/$m^3$ to 12 $/$m^3$] for seawater desalination, and of 2 SR/m^3 to 8 SR/m^3 [about 0.75 $/$m^3$ to 2.02 $/$m^3$] for tertiary treatment of waste water.

Water supply schemes in these areas are often designed for a 50% population growth. This ensures that the system will not become incapable of meeting the increasing demand for some years. By then, closer estimates can be made as to both population growth and water demand. In the present case of the Tihama Asir area, it is perhaps more useful initially to look at the area and determine the space that is available for physical expansion, by a closer examination of the present land use, and approximate population densities can be calculated. Also, ratios of irrigated agricultural land per household can provide useful estimates of the area of land required by further households in order to be self-sufficient.

As waste water treatment plants become more widely used in Saudi Arabia reuse of treated water will play a more prominent role as a source of supply. The treated waste water was already being used for certain industrial and agricultural purposes on a limited scale (see Chapter 5). It has been estimated that by the year 2000, approximately 40 per cent of the water used for domestic purposes in large cities could be available for reuse after treatment. Figure 7.6 charts future water demand in KSA, and estimates urban water demand in cities and towns for the years 1990-2000. The figure reveals projected water use patterns in Saudi Arabia, as well as illustrating a fairly narrow spread from the mean values of the production. Production is shown to be higher in the eastern region, probably due to the environment and more rainfall compared to the northern region, where it is consistently lower because of the absence of fully developed urban infrastructural systems. Another recent, but largely unsubstantiated, urban use of water projection may be derived from the MAW and SWCC.

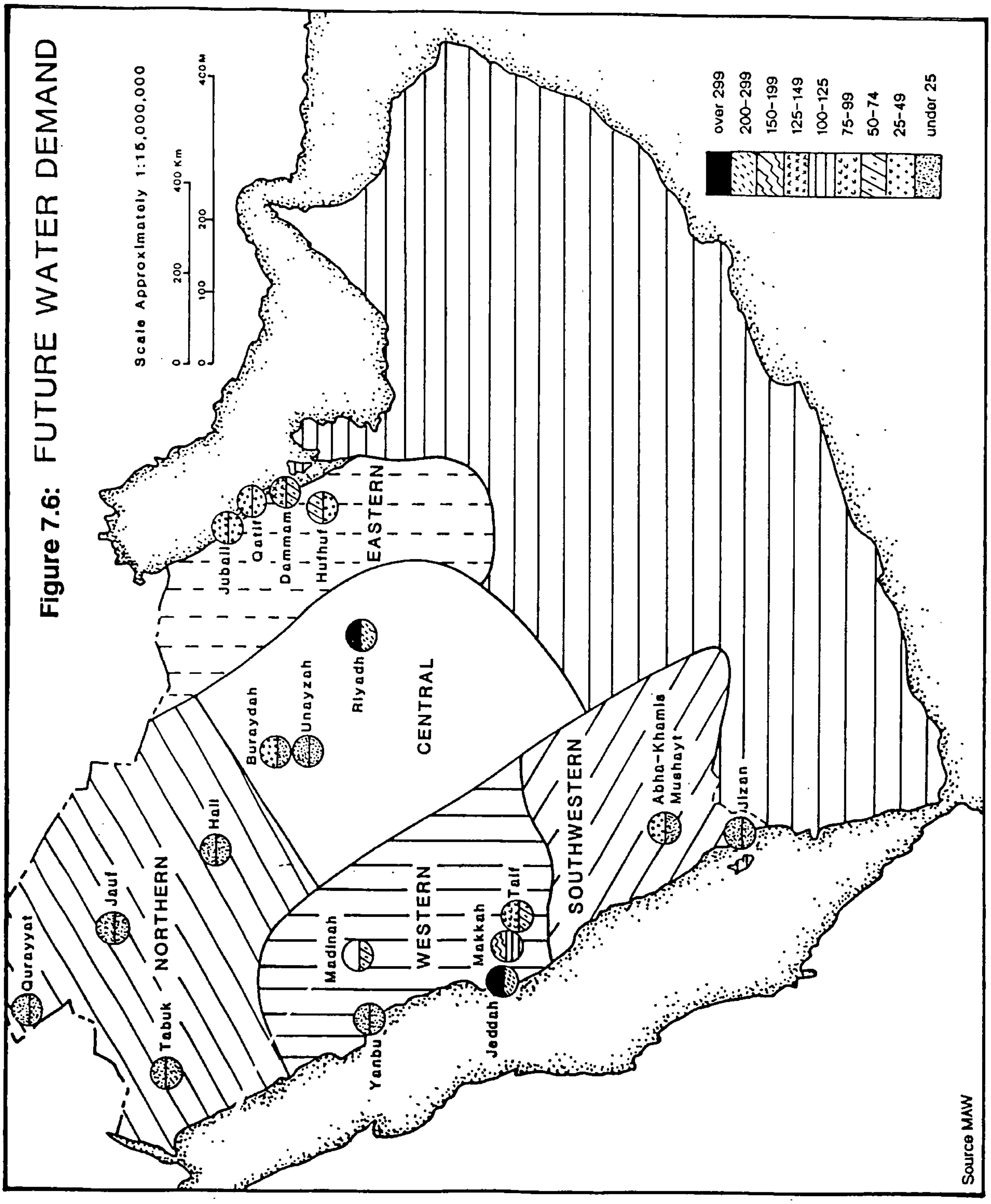


Figure 7.6: FUTURE WATER DEMAND

Average *per capita* demands of 0.359 m^3/d in 1990 and 0.4 m^3/d in 2000 may be derived from the Ministry of Planning.

Figure 7.6 shows the ongoing rapid economic development in the country, the demand for water is steadily increasing. Despite efforts to develop alternative water sources (mostly by tapping groundwater and desalinating sea water), a growing deficit between the demand and the supply of water is becoming apparent. This deficit is estimated to be over 299 mcm. The western region in particular suffers a greater water shortage because four of Saudi Arabia's largest cities are located in the region. These cities are Makkah, Medina, Jeddah and Taif. The Saudi's other regions are the same thing in the western region for the water demand and largest of cities. The government has concentrated its strategies and efforts on tapping groundwater and constructing desalination plants along the coasts, but there has been relatively minor attention devoted to other possible water resource development projects. An overall plan for water management must be devised to increase the efficient use of the country's scarce water supply and to decrease the rate at which non-renewable water resources are being depleted. If similar reduction to this could be made in the urban areas of the country, then clearly the required expansion in the desalination capacity would be reduced which would again make the task of balancing supply and demand in the regions a somewhat more feasible proposition. This observation certainly does seem to be borne out in the context of Saudi Arabia where rulers do seem to find it politically difficult to introduce water use restrictions. Moreover, in many instances there is a distinct unwillingness to do this, because the provision of free or cheap water is seen as one way of indirectly disseminating oil wealth throughout the community and in the case of agricultural and rural areas, charging for water is seen as placing another burden on an already frail sector of economy and society at a time when governments are trying to encourage growth in that sector.

In the same figure, it is shown that the regional ratio of estimate to future water demand units is large in some regions and small in others, for example, the central region has the largest cities in Saudi Arabia such as the capital, Riyadh, the growth of the population, and its industrial and agricultural areas. In the western region lie the Holy cities of Makkah, Medina and Jeddah. In the eastern region lie the petroleum cities, and in the northern and southern regions lie agricultural and rural areas.

Seemingly due to the possibility of rain water cultivation or by flood diversion, the ground water resources are practically unused in the area and the farmers ignore the cultivation possibilities.

Water is a subject of vital importance to the future development of the Tihama Asir. However, due to the geological climate, water is neither freely available, nor easily stored. There are, nonetheless, some areas where renewable groundwater stocks and associated catchment areas are extensive enough to support sizable populations with a modest average *per capita* consumption of a few hundred thousand people with about 0.1 m^3/person/day. It is doubtful, however, if any such new areas remain to be discovered.

The specific urban water projects which are currently planned can be summarised as follows:

- Wells, transmission and treatment systems in Riyadh giving increases daily capacity of 120,000 m^3.
- Work on distribution systems in Jeddah and Al-Kharj.
- Development of Wadi Turabah and provision of additional water supplies to Taif, Hada and vicinity of 17,000 m^3.
- Supply systems of 120,000 m^3/d capacity for Medina, Badr and Al-Musayjid.
- Village supply systems in Qunfudhah.

- Numerous other new systems of extensions in large towns and smaller communities.

A water development census is carried out in KSA every ten years. This permits reliable forecasts to be made to detect the changes in population growth and water demands for every city and village. The government is able to plan and carry out development projects concerning the entire population and for the agricultural and industrial aspects.

The expansion of the KSA water supply was largely affected by the increase in the number of wells that produce from aquifers.

Desalinated water, rather than the existing municipal supply, is greatly needed in various regions of KSA, because demand in the summer months exceeds supply. Water demand forecasts for KSA which had been a variety on projections of total population and *per capita* consumption indicated that an estimated more than 30 mcm/day would be needed in 1991 and 70 mcm/day for the year 2000. Thus, existing wells and desalinated sea water will furnish an adequate supply of water for KSA up to the year 2000 and beyond. Waste water treated for reuse was slowly integrated into KSA's agricultural and industrial water supplies. Projections of ground water and desalinated water supplies showed them to be sufficient to meet Saudi's drinking water demand into the twenty fifth century.

The waste water pilot projects for irrigation were designed to utilise about 3.97 mcm/day in 1990, and expected in the year 2000 to rise to more than 8 mcm/day. Only about 5.97 mcm/day was to be used for irrigation and recharge of aquifers. The remainder was to go to the industrial and recreational requirements. There is a need to establish green belts throughout KSA for aesthetic purposes and for the protection of cities from sand encroachment. It was further estimated that the water requirement for maintaining green spaces would be 3,796,645 m^3 in 1990 and 8,975,655 m^3 for the year 2000.

7.9 Water's future in Tihama Asir

The development of water resources of Tihama Asir was initiated about 10 years ago with the construction of the Malaki dam, east of Abu- Arish, and the development of irrigation structures in the Wadi Jizan and Dammad plains. Very important works are planned for the next ten to fifteen years amounting to approximately SR3 billion (about £410 million/$800 million).

The Tihama region has been divided into four water resource areas. These areas are independent hydraulically and consequently, if demand exceeds supply in any one region there is a problem.

The total water resources of the Tihama Asir amount to about 500 mcm for an average year. Some of this water infiltrates: presently nearly 20% or 98.1 mcm. Out of this only 77.7 mcm are retrievable by pumping, the rest flows into the sea. The existing surface storage of 80 mcm represents 16% of the total runoff.

The amount of water controlled by dams could reach 70%, 355 mcm. Infiltrations in the aquifer would be increased by nearly 25%, and the extractable resources by pumping would increase from 77.7 mcm to 97.1 mcm.

There needs to be development of Wadi Jizan, Wadi Dammad and Wadi Baysh and provision of additional daily supplies to Jizan City, Sabya, Abu-Arish, Baysh, Al-Darb and Dammad and vicinities of 120,000 m^3.

However, the emphasis on water resource development so far has been too much on providing additional water supplies solutions. This approach has tended to concentrate only on one side of the water equation, increasing water supply. Nonetheless, it is argued that if any lasting solution to the problem of water shortages is to be found in Tihama Asir then a more balanced approach must be adopted which will seek to reduce demand as well as increase supply. Of course, efforts to do this might not be popular among many sections of the population of Tihama who are becoming more and more used to increasingly water intensive life-styles. However, the water supplies are simply not available to accommodate the projected demand, many barriers exist which will restrict the ability of Tihama Asir to develop water resources to the level required to meet future demand.

The effectiveness of realistic water pricing policies in Tihama Asir has been illustrated as the number of irrigations make farmers more careful in their use of water.

The development of the Tihama Asir could proceed by several stages during which the future water users would be trained in the following:

1. creation of experimental gardens, irrigated by pumped wells;
2. intensive development of groundwater resources and
3. large scale use of surface water.

The guidelines for water development can be summarised as follows:

1. Emphasis on ground water for inland supply and desalination water at coastal locations.
2. Large industrial users of water to be located near the coast.
3. Increase of agriculture and mining use to take second place.
4. The improvement of water quality.

Control on the extraction of ground water is required. Restrictions can be placed on the number of new wells drilled. Such a system exists in Tihama Asir at the moment.

The number of wells being drilled is still too high and elsewhere a strict licence system might help to alleviate the pressure on ground water.

The introduction of dual quality water distribution systems such as that presently operating in Tihama Asir would also help to reduce consumption of freshwater. In this, the system provides drinking water and brackish water separately which allows the people to use the poorer quality for flushing toilets, washing cars, quenching the thirst of livestock and agricultural irrigation, thereby leaving good quality water for drinking purposes.

With regard to agriculture, the construction of dams to supply water directly and to recharge aquifers should continue throughout the area. Nevertheless, dam construction has only limited success unless it is part of a wider rural development project such as Jizan. This is necessary in order to encourage settlers to move in and to attempt to ensure that water is used as part of more modern irrigation and agricultural systems.

The real future of agricultural water supplies in Tihama Asir lies in the development of effort to modernise agriculture and rural society which will pave the way for a more coordinated and rational approach to water extraction, conveyance, application and drainage.

The cost dimension of creating a balance between supply and demand involves several components. On the basis of the best available information those components have been combined to form the purpose of assessing the scope for residential water conservation. The uses may be classified according to several criteria, the target demand category can serve as a basis for quantifying conservation potential which was used for all modelling runs. Future researchers may wish to modify this matrix if and when inflation becomes a significant parameter of the Saudi economy, or when major changes are made in the subsidy structure. Other modifications will be in order if there are major breakthroughs in production technology, or if a significant delay in the depletion data of fossil groundwater could be achieved.

The emphasis on water balances tends to obscure various, and varying, costs involved in mobilising different resources to satisfy different demands. The most basic component of the cost structure is the cost of supplying raw water, with or without transportation through one of the usual engineering conveyance systems, such as pipelines. Production costs are reported to be in the range of 0.5 to 1.5 SR/m^3 [about 0.01 to 0.5 $\$/m^3$] depending on depth to groundwater, height of water towers, and efficiency of the equipment.

It should be noted that the true cost to the economy should take into account the fact that charges for electric power, the major input in production and transportation are themselves part of a subsidy scheme. Therefore, the true magnitude of the cost component is most likely being underestimated in the study as well as by water products.

In Tihama Asir, the production of agricultural commodities and livestock has been among the key objectives of the government policy. Since scarcity of water is the primary hindrance to the development of agricultural projects, an ambitious programme was launched by the government to overcome this obstacle. The programme includes supplies for ground, surface water, construction of dams, irrigation and drainage networks.

The water development is expected to rely on the wadis resources for several years to come, and extraction from these sources should be increased. Water needs are calculated on the basis of 0.25 m^3/person/day. In 1974, the population was 600,000. This would put the needs for 1990 to be about 150,000 m^3/day. However, the population increased to 1,155,000. The MAW established the existence of a significant quantity of quality well water in the area which can produce 90 mcm/minute at depths between 10 m and 60 m. The total number of wells in Tihama Asir is 8,000 of which more than 30% are equipped with engines and pumps.

Water projects in Tihama Asir include construction of reservoirs, installation of pipes connecting water wells to the reservoirs and the main distribution network is expected to be executed in the near future.

Another problem is that the salinity of water increases with extraction. Salinity in Wadi Sabya, for example, is expected to rise to 250 ppm over 30 years. It will therefore be necessary to control drilling wells and building more dams in Tihama Asir wadis in order to store water to about 81,081,081 mcm/day.

7.10 Conclusions

A comprehensive methodology has been presented for planning water resources and developing water demand alternatives using Saudi Arabia. The methodology utilises a planning tool called the input-output system. This methodology attempts to integrate the hydrologic and socio-economic aspects of water resources planning in the country of study and to provide a system for prediction. The potential of water use in Saudi Arabia was established using water resources control, the productivity of land, labour and capital investment in developing countries. The economic growth of these regions requires access to reliable sources of water to support the various use sectors and to satisfy quality and quantity requirements.

1. The demand sector with the least elasticity is the domestic use. A public awareness campaign, together with the introduction and enforcement of a realistic pricing structure is expected to reduce domestic use to a realistic level.
2. The major problem facing Saudi water resources managers is the uncontrolled expansion of irrigated agriculture. Technology efforts at introducing water-sav-

ing techniques may curtail this demand by as much as 30%. The more important decisions need to be taken on a political level, and it is obvious that any such decisions will have a chance of being implemented only if the water resources development functions are clearly separated from the use functions, regardless of the purposes of the uses.

3. Demand management in Saudi Arabia is a fairly recent phenomenon, even though it presented as one of the objectives to conserve and develop the present known water resources efficiently.

4. There is also a projection of water balance through the year 2000. This candidly faces the problem when it states that whilst the need for water conservation prevails, it is important for the water sector to orientate more towards resource development.

5. The most recent statistics on actual water use are representative of demand in Tihama Asir from the wadis, and have been roughly estimated as indicated in the tables below. They show that compared to water use over the past few years, the agricultural use of water is set to increase much faster than use in urban areas.

Usage	Volume of water (m^3)
Towns supplies	66,000
Agricultural purposes	88,700
Total	154,700

It may be argued that a reasonable supply of water for domestic use, and for ornamental/irrigation, is of direct physical and emotional benefit to people, whereas water for irrigated agriculture is not. Arguments other than hydrologic and economic thus figure prominently in such a discourse and its cost will be considered.

The water provides the following estimates for 1990 demands and supplies:

Demand	Volume of water (mcm/y)
Agricultural demands	3,430
Domestic	1,400
Surface Water Supply	755
Ground supplies	950
Total demands	6,530

6. Agriculture water use is considerably greater than domestic water use. This is because water is consumed for cereal crops and vegetables, and the domestic increase in demand for water is for the annual number of urban houses connected to the supply. All water demands are presently met from ground and surface water, totalling 1705 mcm/y.

However, recognising the limitations most likely to be imposed on this resource because of high temperatures, transportation, costs, salinity and pumping lifts, it is prudent not to boost the estimate. On the basis of earlier resources surveys it was estimated in 1988 that the following amounts replenished the area's water reserves:

Recharge of shallow alluvial aquifer	980 mcm/y
Direct use of surface runoff	1755 mcm/y
Total	12735 mcm/y

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

Presently extensive efforts are being made throughout Saudi Arabia to conserve and develop additional water resources. Saudi Arabia is undergoing rapid economic, demographic and social changes which are the consequences mainly of the vast amounts of oil revenues that contribute to the country's economy.

These abrupt changes have brought about an unanticipated demand for water which cannot be met by the scant local water supply sources that rely mainly on runoff, and groundwater. The problem is becoming more and more acute as the country develops. Several extremely expensive government projects have been implemented to provide water to different parts of Saudi Arabia.

This research has determined the water resources, and domestic and industrial demand and use in Saudi Arabia and Tihama Asir, including desalination and recycling which are used for urban and industrial purposes in Saudi Arabia, though not in Tihama Asir.

Although the supplies appear to be large, the level of water storage, which has risen from 3,280.8 to 32,808.4 mcm, can be used untreated even for agriculture. The most important and urgent to be developed and effectively utilised and conserved are sources vital to life, in such a way to ensure continuing supplies for the present and future.

Several conclusions may be drawn from the results of this study, as shown below.

1. The problem of water shortages in Saudi Arabia is the result of increased urbanisation and industrialisation and a great water demand per capital, rather

than a shortage of the resource per se. With increased growth of major cities in the country the exploitation of more remote groundwater resources has occurred, although groundwater recharge is occurring, it is inadequate to meet the growing demands of the country. However, the development of these two sectors, especially agriculture, requires adequate water supplies. Improved quality and increased quantity of water is also necessary for domestic purposes. New sources of water are, therefore, needed, because future water resources are so significant, it is of utmost importance that economical and efficient measures be taken now to conserve and develop the country's water sources.

2. Regarding water resources, more stability in the data base may be expected since the natural supply of water is only in a minor way subject to development activities. The study illuminates various resources, and should give the layperson a basic understanding of Saudi Arabian water problems. However, the presented data is only summarised, general and incomplete.

   The need for potable piped water will continue to grow as urban areas grow in the country. The need for water is going to continue, the development of these water resources will be a continuous task.

   However, the water problem in Saudi Arabia has been accompanied by inadequate management and conservation measures. Rules and regulations concerning the use of water are not strictly applied. In urban areas, a progressive system of tariffs has been introduced to restrict the over-use of water.

3. From the study of the climate conditions it has been found that there are considerable variations in the climatic characteristics between most of Saudi Arabia on the one hand, and Tihama Asir on the other. The monsoon climate of Tihama Asir degenerates into various kinds of desert climates. It is over Saudi

Arabia that the dry air of central Asia, the moist air of the Mediterranean, and the humid air of the Arabian Sea meet.

4. The improvement of soil and the abundance of water have made intensive cultivation possible in the Tihama region, and greatly improved the contribution of this region, compared with the agricultural production in Saudi Arabia in general, which is limited both in quality and quantity.

5. There are points which stand out clearly and have a direct bearing on the development. There is a vicious circle which, if not checked, will lead to a serious ecological deterioration. Shrinking profit margins are forcing people to abandon agriculturally marginal land. This will lead to soil erosion, and the loss of moisture and vegetation, as has been proved time and again.

6. With the discovery of the artesian water, the huge flowing quantities and reasonably good qualities for irrigation, water used to be a limiting factor for the expansion of the cultivated areas. The serious limitation has shifted to the soil factor, and all present and future agricultural development plans have to be correlated to soil suitability. However, due to local circumstances, the swift shift from agricultural economy based on water to one based on water surplus has brought a complexity of problems relating to the application and utilisation of the artesian water, soil water logging, soil salinity and drainage problems.

7. Surface water sources are limited as it has been indicated and these are mostly located in the western and south western regions (including Tihama Asir) of the country. This source constitutes about 10% of the water resources, and its development requires the building of dams in the wadi catchment. Many of these dams have been built, but more are needed. The total capacity of this water source which can be developed by building more dams reaches 900 mcm/y.

Groundwater sources constitute 11% of the total requirements of water. This is groundwater found in sedimentary layers in the wadi catchments which are replenished by rainfall and groundwater seepage.

The non-renewable sources of water exist in aquifers. This source constitutes more than 70% of the required water. The reserve of this source amounts to 337.5 bcm/y.

8. Availability of adequate quantities of water is one of the most important factors in Saudi Arabia. The four sources of water are rainfall and runoff, groundwater, desalinated water and sewage water. To ensure an adequate supply from these sources for different consumption uses, extensive hydrological surveys and studies to discover new sources of groundwater have been undertaken; a great number of concrete and earthfill dams have been constructed.

9. Saline waters in the wadis of Saudi Arabia, the ways in which they were formed, however, may differ. At this stage, the boundaries of the saline water are not exactly defined. In order to avoid future damaging effects on the aquifer that may result from the spreading of the saline water.

   The supply of domestic and industrial water is a much more difficult problem because many towns are situated in areas where the groundwater reserves cannot be easily tapped and, in these cases, the Saudi Arabian government has decided to make use of its coastal waters by means of desalination techniques.

10. Desalination waters constitute about 10% of the total requirements. Twenty three desalination plants have so far been established, seventeen on the Red Sea and six on the Arabian Gulf, producing nearly 500 mcm/y. It is used mostly for households in the cities. 70% of the requirements of this water had been completed.

11. Recycling of water is still in an infant stage, although it constitutes 1% of the requirements, it needs careful treatment and control. This source amounts to around 100 mcm/y.

As Saudi Arabia becomes more dependent on the technology of desalination, to provide a large portion of the country's water needs. Also, if desalination plants were operated to full capacity and on a more regular basis, and if all plants operated for the dual purpose of providing water and electricity, the cost of producing water would be reduced. Adequate and precise studies are desperately needed to determine the volume of existing groundwater, to ascertain exactly the volume of water being tapped every year, and to determine the rate at which fossil groundwater is being depleted.

12. With regard to urban development, there are severe constraints on the development of big cities. Water shortages, limited agricultural land, distance from the sea (in the context of sea-water desalination), sewage water should be managed in such a way so as not to contaminate urban groundwater.

To increase the efficiency of the country's limited water resources and to reduce the depletion rate of non- renewable groundwater, an optimum overall water development plan is necessary. This plan includes the re-use of waste water, which is an alternative partial solution to the country's present water problem. This source of water, is abundant within the country. However, Saudi Arabia's urban areas are growing steadily, and as the country becomes more urbanised, the idea of waste water re-use seems more appropriate. Various uses of waste water would be prudent, including agricultural irrigation and industrial purposes. However, utilising waste water necessitates a well developed sewage network system which, until recently, has been developed in only a few major cities.

13. The intention of the study was to determine the most dependable and practical water resources to meet cities' domestic and municipal water needs. The cities having undergone rapid growth and massive development, water demands have also increased greatly. The groundwater resources therefore have been developed in order to meet increasing demands and maintain the areas' growth rates.

14. Agricultural irrigation accounts for 84% of the total water demand. The quantity of water consumed by agricultural irrigation increased from 2,000 mcm/y to 7,430 mcm/y, 70% of this water comes from groundwater.

15. Traditional methods of irrigation, such as flooding, are still widely used, causing a waste of this valuable resource and increasing the salinity of soils and water. Efficient water systems such as pivot sprinklers and drip irrigation methods are used, but only by a few producers. Efforts have been made to encourage wider use of these random irrigation systems by providing interest-free loans, but because such systems are expensive and require special skills to operate, their use is still limited.

    All parties who receive water allocations should be required to exercise efficient and economical use of the resource. For instance, farmers should employ the more economical irrigation measures of the drip system or sprinkling. These methods use the same amount of water that is now being used for cultivation but with the ability to cultivate more land.

16. In the cities, many houses have cesspools, and the municipalities carry out a sewage collection service by tanker one single municipal from the cesspool. However, they dispose of the sewage directly onto the ground without treating it. This system is not good for future growth of the cities. The government will be planning for the sewage pipe system and treatment plants in Tihama Asir,

such as Jizan and Sabya are now underway, but integration of the systems into a master plan of the cities faces a serious problem.

17. The policy must be carried out which allows for no further depletion of water supplies unless a programme has begun to gradually phase out this use. Furthermore, studies related to water demand and consumption throughout the country should be conducted to achieve better national policy planning.

8.2 Recommendations

The intent as a result of the study is to determine the most dependable and practical water resources to meet Saudi Arabia's needs. This is due to the lack of accurate record data and to the development of the water demand, domestic water and supply water. Therefore, the following proposed recommendations can be submitted:

8.2.1 Recommendations: KSA

1. Shallow aquifers be used exclusively for the towns' water supply because of their low water development costs. This has become standard practice in water planning of water balances. The current economic development is inviting renewed emphasis on costs.

2. Whilst desalinated water should continue to be a water source, other water resources should be developed for their dependability and economic advantages. The naive assumption is that the problems of water shortage will be banished by the construction of desalination and treatment plants.

3. Maximum advantage of treated sewage effluent should be made. It is, and should continue to be, considered a useful and practical source of water comparable to the aquifers. Treated sewage effluent should be used for irrigation for forage crops and livestock production. Treated effluent for industrial uses also should be given high priority since treated sewage used by industry can be

recovered and recycled many times. Treated effluent should be made available for irrigating plants and shrubs for landscaping and for development for building houses and using in houses and washing cars.

4. Due to Saudi's rapid expansion and because the current major water resources, the distilled seawater, and other resources will satisfy water needs only until 2020, controlling the growth of the cities seems to be the most effective solution to Saudi's water supply problems.

5. Because of the tendency of Saudi people to use excessive amounts of water, several measures that could contribute to reducing excessive use should be undertaken. Public awareness campaigns to bring to the attention of everyone the importance of water and the necessity to conserve this valuable resource should be carefully designed and implemented. Efforts should continue to provide an adequate source of water for different uses. Increasing attention should be directed to utilise more sewage water after chemical treatment for agricultural uses near large urban areas.

6. Efficient use of water should be rewarded by financial incentives and wasteful use should exact penalties. The present low cost of water should be increased to promote conservation and to make the Saudis more concerned about water shortage, especially when used water more than other. Widespread use of mass media, school curricula, billboards, and distribution of water education literature should be implemented to increase public awareness about the water shortage problem and the necessity for water consumption.

7. The irrigated agriculture is the largest user of water in the country. It is essential to educate the farmers about the amount of water required in order for crops to achieve optimum growth.

Farmers tend to use as much water as is available, even though over-watering may result. Therefore, an effective way of controlling the farmers' water use should be instigated to encourage efficient application.

8. The water policy to increase the efficiency of the country's limited water resources and to reduce the depletion rate of non-renewable groundwater and surface water supplies, are essential to Saudi Arabia's future development.

8.3 Tihama Asir: Specific Observations

This study concerns the water resources in the Tihama Asir. During the study I had the opportunity to investigate at a close range the present water resources as well as the progress and effects of the recent water resources development in the area. This period also gave me the chance to discuss directly their impressions of the development of water resources problems. As a result of this investigation, regarding water problems in the Tihama Asir area, the following shortcomings are to be pointed out:

1. The wellfield has no protective perimeter fence, and is threatened by construction above it. *Per capita* daily production is fairly low. Shortages, which imply a rationed service, increase the risk of contamination of an emptied reservoir.

   The available storage capacity of 300 mcm is far below the minimum required one-day consumption. Seepage rates are high. The network serves only 75% of households with an unmetered service. There is no continuous chlorination. There is a lack of right-of-way and bench-marking for the feeder pipes, which run along the airport runways.

2. At the present time Tihama Asir is undergoing rapid economic development and, as a consequence, demands on water resources are going. By careful development and management of the huge groundwater reserves, it would seem that the agricultural demand for relatively cheap water for irrigation can be met

for sometime into the future - even increase rates of usage could possible be met. The supply of domestic and industrial water is a difficult problem because the inside towns are situated in areas where the groundwater reserves cannot be easily tapped, and, in the cases the MAW has been pumping for carrying to ensure that this does not occur. The population is quite heavily concentrated, physical, climatic and soil conditions in the area are favourable for agriculture. The core of this demand is essentially the development water resource in the area through wise central and effective use of flood waters, for domestic, industrial and agricultural uses. The new irrigation system, modern civilisation techniques, greater crop diversity, and increased land use. Two main themes are apparent in the wadis agricultural development projects, such as Wadi Jizan and Wadi Dammad. The first and most important is that the project is considered an essential step toward comprehensive agricultural development for the area. The second is that the wadis area are intended to be a prototype for the other.

3. In addition to the available surface wand, an aquifer was discovered in the area, thus groundwater can also be utilised. However, the pressure of such cities as Jizan City on the coast of the Red Sea. and Abu Arish, both of which have potential for growth and expansion, presents areas for marketing centres. Such towns would also help consume the increased demand for water from wadis. Such a move for development would, in time, supply the serious destruction of houses and land which occur in Wadi Jizan from high flood water, after a dam is built. Although, the dam has improved the water scarcity problem somewhat, as the available surface water is dependent upon rainfall, it various from year to year.

4. There is insufficient reservoir capacity in the area for peak-time consumption and fire-fighting. Borehole equipment is inadequate or deficient: diesel engined

motor pumps; and there are no non-return valves, manometers, water meters and level meters. Some of the pipes are less than 1000 mm in diameter, and do not meet the pressure and flow requirements for fire hydrants.

5. Water resources are rich in the Tihama Asir, compared with other parts of Saudi Arabia, and considerably utilised mainly for the agricultural uses.

   Piped water supply systems are functioning only in the cities of Jizan and Abu Arish, but the system is the direct supply from the wells without purification. In other villages and towns, water is supplied privately by tanker trucks from wells.

6. The network in the following towns will be designed and constructed: Abu arish, Jizan, Sabya and Samtah. Furthermore, regarding the small communities, projects will include drilling, repair and replacement of wells, and the construction of distribution systems, to improve the quality and accessibility of the supply of water for domestic use and the watering of animals. For the recharge of shallow aquifers, irrigation and flood control some more small dams will be constructed.

7. A sewage system is definitely necessary and important to improve hygienic conditions of the Tihama Asir. There is no sewage pipe system in the area. Even in the cities, and some pour sewage directly into the streets. Such practices are not only unsightly, but create unsanitary conditions.

8. The layout and structure of the network are inadequate, which results in leakage, rupture and contamination. These leakages are one of the main sources of underground cavities in the salt dome. Improving the quality and volume of the supply and the distribution system by developing a complete interlooped distribution network would require starting with new ground service reservoirs.

8.4 Recommendations: Tihama Asir

1. Shallow aquifers should be used exclusively for the towns' water supply because of their low water development costs. There are various costs involved in mobilising different resources to satisfy different demands.

2. Other current groundwater users in the wadi, such as farmers, should benefit from one of the following:

   a. Monetary compensation, or an offer of farmland in another area.

   b. Farmers in the area of wadis should be allowed to drill wells into the aquifer.

3. For maximum advantage of groundwater use, farmers should be encouraged and advised to use the most advanced irrigation methods and techniques to reduce overflow and water evaporation as much as possible.

4. Medium sized floods are most common in the area and large quantities of its water runs downstream from the wadi. Because only a small amount of water is absorbed into the ground, dams and flood retarding structures should be constructed to enhance the recharge. Most prevalent is the problem of water scarcity. The present water distribution system borders on the archaic, and is simply not practical. Such a system needs to be completely revised, and a more even distribution pattern should be developed. In addition, further exploitation of groundwater is recommended in order to lessen the dependence on rainfall in the area. The dam, although greatly improving the amount of water stored and decreasing the amount of water lost, can do nothing to increase the amount of surface water available.

5. The volume of groundwater pumped from aquifers should not exceed the average recharge rate in order to maintain continuous supply and to avoid water quality deterioration.

6. To compensate farmers who use less water for irrigation and who eliminate water dissipation, a tax quota system should be established. This system could be applied by assigning a fixed allowable quantity of water for each acre. Farmers could exceed or fall below their quotas, but each farmer is assessed for tax according to the quantity used compared to his quota.

7. A differential rate structure for water prices should be established to eliminate unnecessary use of water. In order to decrease water consumption, the government should reduce subsidies so that consumer prices are closer to the actual costs of water supply.

8. Strengthening the existing water-management system to make it more effective in regulating and scientifically co-ordinating the use and construction of water pumps in accordance with land and water topography.

   Efforts should continue to provide an adequate supply of water for the different uses. Increasing attention should be directed to utilise more sewage water after chemical treatment for domestic, industrial and agricultural uses, to improve substantially the quantity and quality of the water supply, a treatment plant at the well field should be erected allowing for convenient water softening and disinfection by treating one half of the daily volumes and blending treated and raw water.

Bibliography

Books

Abdulaziz, M.H., *Principles of Hydrology*, Riyadh, King Saud University, 1984. In Arabic.

Abdulaziz, M.H., *Water Requirements of Important Crops in Saudi Arabia*, Riyadh, King Saud University, 1986. In Arabic.

Abdulrazzak, M., *Water Conservation in Arid Lands*, Dhahran, R.L. de Jeng, ed., UPM Press, 1986.

Abu-Alainine, H.A., *Geomorphology*, Beirut, Dar Al-Nahdah Al-Arabia, Fifth Edition, 1979. In Arabic.

Abu-Alata, H.H.F., *Water and Climate*, Alexandria, Dar-Al Ma'arifa Al-Jama'ayah. In Arabic.

Abu-Alaulae, M.T., *Geography of Arabian Peninsula - Saudi Arabia*. Cairo, Mu'assah Arabian syjel, Third Edition, Vol.2. In Arabic.

Agnew, C. and Anderson, E., *Water Resources in the Arid Realm*, London, New York, Routledge, 1992.

Al-Barodie, M.S., *Water Budget and Wadi Fattema*. Kuwait, Geographical Society, 1988. In Arabic.

Al-Brazi, K.N. & Al Mashhdani, I., *Agricultural Geography*, Baghdad University, Second Edition, 1985. In Arabic.

Alexander, Martin, *Beginning of Soil Microbiology*, England, John Wiley & Sons Ltd., 1982. In Arabic.

Al-Farssy, F., *Saudi Arabia: A Case Study in Development*, London, Kegan Paul International, 1982.

Al-Ghanim, Y.A., *Physical Geography*, Kuwait Geography Society, 1981. In Arabic.

Al-Hamdani, Ahmed, *Suff Jazirat al Arab*, H. Al-Jasser (ed.), Riyadh, Dar Al-Yamamah for Translation and Press, 1974. In Arabic.

Al-Khatib, Farouk, S., *Water and Regional Development in Saudi Arabia: An economic analytical study*, Jeddah, King Abdulaziz University, 1986. In Arabic.

Al-Marshoud, F. & Jared, A.K., *Water Re-use in the Kingdom of Saudi Arabia*, Riyadh, Ministry of Agriculture and Water, 1982.

Al-Matari Al Sayid, K., *Biological Geography*, Jeddah, Al-Dar Al-Saudiah, 1981. In Arabic.

Al-Matari Al Sayid, K., *The Study in Islamic World of Population*, Jeddah, King Abdulaziz University, 1984. In Arabic.

Al-Bana, Ali *Beginning of Geography, Climate and Vegetation*, Beirut, Dar Al-Nahdah Al-Arabia, 1970, in Arabic.

Al-Ruwaithy, M.A.H., *The ports of Saudi Arabia on the Red Sea Coast - A study in Economic Geography*, Cairo, Al-Medeni, 1984. In Arabic.

Al-Shalash, A.H., *Geography of Soil*, Iraq, Basrah University, 1985. In Arabic.

Al-Shalash, A.H., *Climate of Iraq*, Amman, Jordan, Cooperative printing press, 1966. In Arabic.

Al-Sharif, A.S. *Geography of Saudi Arabia*, Riyadh, Dar Al Marrekh Press, Vol.1, 1977, In Arabic.

Al-Turbak, S.A. and A.A., Quraishi, *Regional FloOd Frequency Analysis for some Selected Basins in Saudi Arabia*, USA, Louisiana State University, Baton Rouge, 1986.

Amer, H.E., *Desalination Glossary*, Jeddah, Saline Water Conservation Corporation, 1978.

Arafah, Mussa, *Asswan's Dam*, Cairo, Dar Al-Ma'arif, 1965. In Arabic.

Assah, A., *Mu'jizah Fauqa'l-rimal*, Beirut, Al-Mattba'ah Al-Ahliyah Al-Bohaniah, Third Edition, 1972. In Arabic.

As-Suqair, M., *The use of treated sewage water for various purposes. Seminar on development and uses for water resources*, Riyadh, Ministry of Agriculture and Water, Riyadh District and Sewage Department, 1982. In Arabic.

Baden, M.R., *The Service Radio Network of the Water Supply System in Riyadh*, Brown Bover, Review of Company, 1983.

Bakur, S.A., *Geography of Hajj Roads*, Jeddah, Tihama Publications, 1981. In Arabic.

Barry, R.G., Chorley, R.J., *Atmosphere, Weather and Climate*, London, New York, Methuen, Fifth Edition, 1987.

Bolts, C.L., *Desalination Problems and Techniques*, London, British Aqua Chem Ltd., 1967.

Bouwer, H., *Ground Water Hydrology*, USA, McGraw-Hill Book Company, 1978.

Chorley, J.R., (ed.), *Water, Earth and Man*, translated by W.H. Al-Khashab, Baghdad, Baghdad University, 1979. In Arabic.

Clarke, J.I., *Population Geography and the Developing Countries*, Oxford, Pergamon Press Ltd., 1981.

Collinson, J.D. and Thompson, D.B., *Sedimentary structures*, London, Unwin Hyman, Second Edition, 1989.

Compton, Robert R., *Geology in the field*, USA, John Wiley & Sons Inc., 1985.

Cooke, Ronald U., and Warren, Andrew, *Geomorphology in deserts*, London, B.T. Batsford Ltd., Second Edition, 1975.

Craig, H., Gordon, J.I., and Horibe, Y., "Sotepic exchange effects in the evaporation of water, *J.Geophys.Res.*, 68:6079-6087, 1963.

Cruickshank, James G., *Soil geography*, Newton Abbot, David & Charles Ltd., Third Edition, 1977.

Cullen, Allan H., *Rivers in Harness: the theory of dams*, translated by Basha, A. Ali, Cairo, Egyptian Maktabah, 1965. In Arabic.

Dansgaard, W., "Stable isotopes in precipitation", *Tellus*, 16:436-468, 1964.

Deming, H.G., *Water*, New York, Oxford University Press, Second Print, 1978.

Devoy, R.J.N., *Sea surface studies, a global view*, London, Croom Helm, 1967.

Dirow, Max, *Geomorphology*, Translated by Hamydh, Abdurahman, Domestic, Dar Al-Feker, 1982. In Arabic.

Dove, H.F., *Developing Water Policy*, Riyadh, Ministry of Agriculture and Water, 1976.

Dregne, H.E. and Willis, W.O., *Dry Land Agriculture*, USA, Madison, Wisconsin, 1983.

Dury, G.H., *World physical geography*, London, Thomas Nelson Ltd., Eighth Edition, 1967.

Dury, G.H., *Essays in Geomorphology*, London, Heinemann, reprinted, 1967.

Eagleson, P.S., "Climate, soil and vegetation", *Water Resour. Res.* 14:713-721, 1978.

Eagleson, P.S., "The distribution of catchment coverage by stationary rainstorms", *Wat. Resour. Res.* 20:581-590, 1984.

Edgintion, R., *Proposal for improving Riyadh City water supplies and storage facilities*, Riyadh, Ministry of Agriculture and Water, 1967.

Ellis, K.V., *Surface Water Pollution and its Control*, London, MacMillan, 1989.

Eyre, S.R., *Vegetation and soil - A world picture*, London, Edward Arnold Ltd., Second Edition, 1984.

Fares, M., Hussein, M., and Yusef, M., *Nurses of geomorphology*, Cairo, Dar Al-Nahdah Al-Arabia, 1976. In Arabic.

Fayed, Y.A., *Structure and Geomorphology - Physical Geography*, Cairo, Dar Al-Nahdah Al-Arabia, 1976. In Arabic.

Feachem, Richard, McGarry, Michael and Mara, Duncan, *Water wastes and health in hot climates*, New Delhi, John Wiley and Sons Ltd., reprinted, 1983.

Feteris, P.J., "The Bab-El Mandeb Gap Winds over the southern Red Sea", *J. Mississippi Acad. Sci.*, XXVIII:143-157, 1983.

Feteris, P.J., and N. Wokolo, B., "Pressure, temperature and wind oscillation over the Red Sea", *J. Mississippi Acad.Sci.*, XXIX:49-62, 1984.

Fiering, M.B., "An optimization scheme for gaging", *Wat. Resour. Res.* 4:463-469, 1965.

Fisher, W.B., *The Middle East*, London, Methuen & Co. Ltd., Seventh Edition, 1978.

Fitzpatrick, E.A., *An introduction to soil science*, London, Longman Scientific and Technical, 1974.

Fitzpatrick, E.A., *Soil, their formation, classification and distribution*, London, Longman Group Ltd., 1980-1983.

Fletcher, N.H., *Physics of rain clouds*, London, Cambridge University Press, 1962.

Foth, Henry D., *Fundamentals of soil science*, USA, John Wiley and Sons Inc., 1984.

Garnier, J. Beaujeu, *Geography of population*, translated by Beaver, S.H., London, Longman, Fifth Impression, 1976.

George, Pierre, *Geography and the Population*, translated by Fakeladeh Samouhi, Beirut, Paris, Editions Oueidat, Third Edition, 1985. In Arabic.

German Consult., *Reports on Agricultural Development of South Tihama*, 1979.

Ghalab, M.S. and Abdulhakym, M.S., *Population demography and geography*, Cairo, Dar Al-Ma'arif, 1986. In Arabic.

Ghodah, G.H., *Land features*, Beirut, Dar Al-Nahdah Al-Arabia, 1980. In Arabic.

Grainger, Alan, *Desertification, how people make desert, how people can stop and why they don't?*, London, Farthscan, reprinted, 1986.

Gregory, K.J. and Watling, D.E., *Drainage basin form and process: A geomorphological approach*, London, Edward Arnold Ltd., 1973.

Gregory, K.J., *The nature of physical geography*, London, Edward Arnold Ltd., 1985.

Grigg, David, *An introduction to agricultural geography*, London, Hutchinson University Library, reprinted, 1986.

Habib, A.M., *Kingdom of Saudi Arabia*, Cairo, Al-Maktabah Al-Englo Al-Massriyah, 1975. In Arabic.

Hammdan, J., *Agriculture of Egyptians*, Cairo, Dar Al-Shoroug, 1984. In Arabic.

Hammer, Mark J., *Water and Waste Water Technology*, Singapore, John Wiley & Sons Inc., Second Edition, 1986.

Hamza, E.A., *Desalination Glossary*, Jeddah, Saline Water Conservation Corporation, 1978.

Hanna, N.S., *Desert People Group in Arabian Countries*, Cairo, Dar Al-Ma'arif, 1986. In Arabic.

Hindy, A.I., *The major strategic characteristics of agricultural development in the Arabian countries*, Alexandria, Al-Ma'aref, 1980. In Arabic.

Hobbs, J.E., *Applied climatology - Studies in the physical geography*, Kent, England, Wm. Damson & Sons Ltd., 1980.

Hollis, G.E., *Man's impact on the hydrological cycle in the United Kingdom*, Norwich, England, Geo Abstracts Ltd., 1979.

Holmes, Doris L., *Principles of physical geology*, England, Van Nostrand Reinhold Co. Ltd., Third Edition, reprinted, 1984.

Ilbery, Brian W., *Agricultural geography - A social and economic analysis*, Oxford, Oxford University Press, 1985.

Ingrams, H., *Arabia and the Isles*, London, John Murray, 1966.

Jones, H.R., *Population geography*, New York, Harper & Row Publishers, reprinted, 1985.

Kahhalah, U.R., *Arabian peninsula geography*, Damascus, Al-Matba'ah Al-Mashiamiah, 1944. In Arabic.

Kay, Melvyn, *Sprinkler irrigation, equipment and practice*, London, BT Batsford Ltd., 1983.

Kay, Melvyn, *Surface irrigation, systems and practice*, Bedford, Cranfield Press, 1986.

Kenzo, Tonge and Urtec, *Southern region project study, existing conditions*, Saudi Arabia, Ministry of Planning and Rural Development, 1976.

Knapp, Brian, *Soil processes*, London, George Allen & Unwin, second impression, 1983.

Kuiper, Edward, *Water Resources Development*, London, Butterworths, 1965.

Lazaro, Timothy R., *Urban Hydrology, A Multi-disciplinary Perspective*, USA, Ann Arbor Science Publishers Inc., 1979.

Leopold, L.B., *Water - A Primer*, San Fransisco, W.H. Freeman & Co., 1974.

Linsley, Ray K., and Franzini, Joseph B., *Water Resource Engineering*, London, McGraw-Hill Book Company, second edition, 1972.

Lockwood, John G., *World climatic systems*, London, Edward Arnold Ltd., 1985.

Lowrance, Richard, Stinner, Benjamin R., House, Garfield J., *Agricultural ecosystems - Unifying concepts*, Canada, John Wiley and Sons Inc., 1984.

Mamanah, S.H., *The material and bruuical geography*, Beirut, Dar Al-Nahdah Al-Arabia, 1984. In Arabic.

Marrii, Sayid, *Egyptian agriculture*, Cairo, Ministry of Agriculture, 1970. In Arabic.

Mary, Marcel, *The Dams*, translated by Chaaban, Bahige, Beirut, Editions Oueidat, Second Edition, 1985. In Arabic.

Mather, J.R., *The Climatic Water Budget in Environmental Analysis*, Lexington Ma, D.C. Heath, 1978.

McGinnies, William G., Goldman, Bram J., and Paylore, Patricia, *Deserts of the world - an appraisal of research into their physical and biological environments*, USA, University of Arizona Press, Second Edition, 1970.

Ministry of Information, *Ongoing Development*, Riyadh, 1984. In Arabic.

Ministry of Information, *Land of Asir*, Riyadh, 1986. In Arabic.

Ministry of Planning, *Second five year development plan*, Riyadh, 1985. In Arabic.

Ministry of Planning, *Fourth five year development plan*, Riyadh, 1975. In Arabic.

Mead, Margaret, and Kellog, William W., *The Atmosphere - Endangered and Endangering*, London, William Clowes Ltd., 1980.

Mohammad, Abu Al-ala M., *Comparative study - hydrological and irrigation between Tihama wadis in Saudi Arabia and coastal wadis in Peuro*, Cairo, Dar Al-Nahdah Al-Arabia, 1985. In Arabic.

McCullagh, Patrick, *Modern concepts in geomorphology*, Oxford, Oxford University Press, Fourth Impression, 1986.

Money, D.C., *Climate, soils and vegetation*, Norwich, England, Fletcher and Sons Ltd., Third Edition, reprinted 1985.

Monkhouse, F.J., *Principles of physical geography*, Kent, Hazell Watson and Viney Ltd., Tenth Impression, 1986.

Nadim, Asaad, Nadim, Nawal, Mehanna, Sohair, Nixon, John H., "Cairo papers in social science - living without water", Cairo, The American University, Vol. 3, Monograph 3, 1980.

Noury, M.A., and Kolthem, M.S., *Production and Distribution of Water in Saudi Arabia*, Riyadh, Ministry of Irrigation and Water, 1981. In Arabic.

Noury, M.A., *Water and Development Process in Saudi Arabia*, Jeddah, Tihamas Publications, 1983. In Arabic.

Oliver, Hendry, *Irrigation and Climate*, London, Edward Arnold Publishers Ltd.

Ordway, Richard J., *Earth science and the environment*, New York, D.D. Van Nostrand Company, 1974.

Pearce, E.A. and Smith, C.G., *The world weather guide*, London, Mermail Book, 1985.

Press, Frank, and Siever, Raymond, *Earth*, New York, W.H. Freeman and Company, Fourth Edition, 1986.

Quilici, Folco, *The great deserts*, London, Collins Publishers International Library, 1969.

Rafa'at, A.M., *The beginning of rock science*, Kuwait, Dar Al-Qulam, Third Edition, 1979. In Arabic.

Read, H.H. and Watson, Janet, *Beginning geology*, London, Macmillan Education Ltd., reprinted, 1986.

Rajab, U.F., *The Geography of Saudi Arabia*, Jeddah, Dar Al Sharuq, 1978. In Arabic.

Rajab, U.F., *Al Hijaz Western Saudi Arabia - Land and People*, Jeddah, Dar Al Sharuq, 1979. In Arabic.

Riyadh District Water and Sewage Dept., *Report on the Operation Process of Riyadh Sewage Project*, Riyadh, Al-Ahilyah Press, 1983.

Saline Water Conservation Corporation (ed.), *Fresh Water from the Sea*, Riyadh, Middle East Press.

Salym, H.R., *The difference of water at desert valley in Jordan*, Kuwait Geography Society, 1985. In Arabic.

Serjeant, R.B., and Bidwell, R.L., *Arabian Study, IV*, University of Cambridge, The Middle East Centre, 1982. In Arabic.

Shabyyjler, K.S., *The purification of salt water*, translated by Al-Sayid, M.M., Jeddah, King Abdulaziz University, 1987. In Arabic.

Shaker, M., *Arab peninsula - Asir*, Beirut, Al-Matba'ah Al-Islamiah, 1963. In Arabic.

Sherif, M.M., *Production economics report to wadi Jizan agricultural development project*, Rome, F.A.O., 1977.

Shuval, Hillel I., *Water renovation and reuse*, London, A subsidiary of Harcourt Brace, 1977.

Siever, Raymond, *Sand*, USA, W.H. Freeman and Company, 1988.

Simon, Julian L., and Kahn, Herman, *The Resourceful Earth*, Oxford, Basil Blackwell, 1984.

Smedema, Lambert K., Tycroft, David W., *Land drainage*, London, B.T. Batsford Ltd.

Sparks, B.W., *Geomorphology*, London, Longman, Third Edition, 1986.

Strahler, Arthur N., *Introduction to physical geography*, USA, Wiley International Edition, Third Edition, 1973.

Thomann, Robert V., and Mueller, John A., *Principles of surface water quality modeling and control*, New York, Harper and Row Publishers Inc., 1987.

Todd, David Keith, *Ground Water Hydrology*, USA, John Wiley and Sons Inc., Second Edition, 1980.

Totysh, T.S., *Kingdom of Saudi Arabia and development of natural resource*, translated by El Aumawi, Shakeeb, Cairo, Dar Ahiya Al-Kotob Al-Arabia, 1955. In Arabic.

Verstraten, J.M., *Water-Rock interactions*, Norwich, England, GEO Books, 1980.

Vidal, F.S., *The oasis of Al-Hasa*, Dhahran Arabian American Oil Company, 1955.

Waheem, Talib M., *The Hijaz Kingdom 1916-1925 - A study of political situations*, Al-Basrah, Matba'at Al-Basrah University, 1982. In Arabic.

West, T.S., Nurnberg, *The determination of trace metals in natural water*, Oxford, Blackwell Scientific Publications, 1985.

Wiener, Aaron (ed.), *The role of water in development*, London, McGraw-Hill Book Company.

Wood, Robert Muir, *The dark side of the earth*, London, Allen and Unwin, 1985.

Yemeni, Mohammad A., *Geology of economy in Saudi Arabia*, UK, George Allen and Unwin Ltd., 1985. In Arabic.

Zimmerman, Josef D., *Irrigation*, USA, John Wiley and Sons Inc., 1966.

Ztiel, Donald, *The geography of soil*, New Jersey, USA, Prentice Hall Inc., 1974.

Reports

"Al Jubayl Phase II Power/Desalination Plant", Report prepared by Catalytic Inc. (Consultants), Kuljian Corporation, Al Jubayl.

King Abdulaziz University, Saline Water Conversion Corporation, University of Glasgow (UK), "Short course on desalination technology", Jeddah, King Abdulaziz University Press, 1980.

Sanderson and Porter Inc., New York, "Al-Jubayl Power and Desalination Facility". Technical report prepared for Saline Water Conversion Corporation, Jeddah, 1983.

Ground Water Development Consultants, "Umm Er Radhuma Study", Riyadh, report to Ministry of Agriculture and Water, 1980.

Italconsult, "Water and agricultural development for area IV", Riyadh, unpublished report to the Ministry of Agriculture and Water, 1969.

Italconsult, "Land and water studies on the Wadi Jizan", 1965.

Development Analysis Associates Inc. (Cambridge, Massachusetts), "Water and power requirements for Saudi Arabia. Application to the control zone of demand projections", report prepared for the Saline Water Conversion Corporation, Saudi Arabia, 1979.

Ministry of Agriculture and Water, "National Water Plan", Vol.1, Water resources of Saudi Arabia, prepared by the British Arabian Advisory Company and the Water Resources Development Department, Riyadh, 1980.

Newspapers and Magazines

ADDARAH, an academic quarterly issued by King Abdulaziz Research Centre, Riyadh, in Arabic.

1. Al-Farra, Taha O., "Sabkhas in Saudi Arabia", Vol.3, No.4, January 1978, page 13.
2. Saleh, Hassan A., "The resources of underground water in Saudi Arabia", by Abdulkadir Saleh and Abdulrahman Al-Sharid, Vol.8, No.4, January, 1978, pages 5-9.
3. Ibn Khamis, A., "Agricultural areas in Saudi Arabia", Vol.5, No.3, March 1980, pages 17-27.
4. Khalifa, Dayed F., "The plant geography of Saudi Arabia", Vol.5, No.2, December 1979, pages 18-27.
5. Al-Sharif, A.S., "The climate of southwest Saudi Arabia", Vol.2, No.1, March 1976, pages 32-33.
6. Al-Shamekh, A.A., "Drainage system into the Qassim region of Saudi Arabia", Vol.5, No.4, June 1980, pages 5-16.
7. Al-Mohandis, A.A., "Underground quality water into Khobar region south of Saudi Arabia", Vol.14, No.1, May 1988, pages 232-245.

Al-Madina Daily, No.7921, Page 4, 11 January, 1988, Jeddah.

Al-Nadwa Daily, No. 8706, Page 10, 15 October, 1987.

Al-Nadwa Daily, No. 7120, Page 14, 21 December, 1987.

Al-Riyadh Daily, No.7057, Page 11, 19 October, 1987, Riyadh.

Al-Riyadh Daily, No.7963, Page 6, 12 April, 1990.

Al-Riyadh Daily, No.7996, Page 5, 15 May, 1990.

Al-Sharq Al-Awsat International Daily Newspaper of the Arabs, No. 3495, Page 5, 23 June, 1988.

Al-Yamamah Weekly Magazine, No.1069, Page 42-46, 30 August, 1989, Riyadh.

Iqraa Weekly Magazine, No.675, Page 62-66, 23 June, 1988, Jeddah.

Iqraa Weekly Magazine, No.753, Page 4-8, 1 February, 1990, Jeddah.

Iqraa Weekly Magazine, No.754, Page 42-43, 8 February, 1990, Jeddah.

Official Publications in Saudi Arabia

Ministry of Agriculture and Water, "Water Resources", Riyadh, 1985.

Ministry of Agriculture and Water, "Water requirements of important crops in Saudi Arabia", Riyadh, 1986.

Ministry of Agriculture and Water, "Agricultural Sector Department", Riyadh, 1987.

Ministry of Agriculture and Water, "Bulletin of Agricultural Current Sample Survey", Riyadh, 1984.

Ministry of Agriculture and Water, "Hafer Al-Batin and Qaisuma water project", Riyadh, 1985.

Ministry of Agriculture and Water, "Delivery of water project from Buwayb to Riyadh City", Riyadh, 1978.

Ministry of Information, "Land of Achievement", Riyadh, 1972.

Saline Water Conversion Corporation, "Proposals Projects", Riyadh, 1984.