DEVELOPMENT OF WATER RESOURCES IN BAHRAIN: A COMBINED APPROACH OF SUPPLY - DEMAND ANALYSIS

VOLUME ONE

by

MUBARAK AMAN AL-NOAIMI

A thesis submitted to the University of Plymouth
in partial fulfillment for the degree of

DOCTOR OF PHILOSOPHY

School of Earth, Ocean, and Environmental Sciences
Faculty of Science

2004

Dedication

to the soul of my father .... with great appreciation.

to my family, Iman, Bader, and Faris .... with great love.

DEVELOPMENT OF WATER RESOURCES IN BAHRAIN: A COMBINED APPROACH OF SUPPLY-DEMAND ANALYSIS

by

Mubarak Aman Al-Noaimi

Bahrain is an arid country with acute water shortage problems. The demand for water has increased substantially over the last four decades, leading to over-exploitation from the already scarce renewable groundwater resources. This has caused a significant decline in groundwater levels, a drastic storage depletion, and serious deterioration in groundwater quality. The imbalance between the available water supply and the projected water demand has been growing rapidly, imposing a major constraint on the country's socio-economic development. Resolving these problems or at least mitigating their adverse impacts primarily requires a major shift from the supply-oriented approach to water planning, which is currently being emphasised, towards a greater emphasis on demand-side management policies. In this thesis, a combined approach of supply-demand analysis is employed to investigate the water and management problems in the study area, with the ultimate objective of establishing a supply-demand analytical framework to aid in the formulation of an integrated water management policy.

The existing water resources are comprehensively assessed in terms of availability and development constraints. The water use patterns and demand characteristics are systematically analysed. The results of these analyses are shown to have important implications from the water resources planning and management perspective. Using data from cross-sectional surveys, separate water demand functions of both linear and log-linear functional forms are estimated for the major water use activities. The empirical evidence presented in this research suggests that certain socio-economic, demographic, physical, climatic, and technological factors affect water use.

The variables household size and household/per capita income are found to be the most important determinants of residential water use, with a priori expected signs. Average price, however, does not have a statistically significant effect. Estimated income elasticities vary from 0.12 to 0.22; household size elasticities range from 0.30 to 0.41. Empirical estimates for summer and winter residential demand functions suggest some interesting findings with respect to the seasonal variability in water use. Per capita income elasticities of municipal demand of between 0.15 - 0.33 are estimated. Both the residential and municipal income elasticity estimates appear to correlate favourably with some estimates found in the literature. Not surprisingly, average price elasticity of per capita municipal demand is estimated to be -0.066, indicating an extremely inelastic demand. In general, the empirical findings from both the non-residential and agricultural surveys give less reliable statistical results, perhaps owing to the insufficiency of data and/or lack of specific explanatory variables. However, the variables number of bathrooms and presence of swimming pool may be adequate indicators of the non-residential water use, while gross cultivated area appears to be the best single predictor of the agricultural water use.

Industrial water demand is shown to be significantly and directly related to the variables measuring production level, number of employees, and factory floor area. Validity tests for the selected analytical models are made.

The water supply and demand relationships are examined and water balances for the specified planning period are computed. The improved trend forecasting procedures provide encouragingly accurate results when compared to the actual water use. Three alternative water management scenarios are developed. Comparison among these scenarios indicates that Scenario C, which integrates the supply and demand management policies, is the most efficient option for achieving optimal water resources development and management. Policy recommendations to enable effective formulation and implementation of this option are presented.

TABLE OF CONTENTS

VOLUME ONE

LIST OF TABLES

VOLUME ONE

Table

VOLUME TWO

Table

LIST OF FIGURES

VOLUME ONE

Figure

VOLUME TWO

Figure

LIST OF APPENDICES

Appendix

Appendix A Meteorological Data

Appendix B Hydrogeological Data

Appendix C Hydrochemical Data

ACKNOWLEDGMENT

I gratefully acknowledge the Bahrain-British Foundation and The British Council in Bahrain for their partial financial support during the early stages of this research. Special thanks are due to my supervisor Dr Kenneth Vines for his guidance, patience, and continual assistance throughout the course of this research. I would also like to express my sincere gratitude to Dr James Griffiths for his support and genuine understanding. Dr Griffiths has also read an earlier version of Chapter Seven and offered thoughtful comments. I am very grateful to Professor Malcolm Hart for his expert advice and kind assistance regarding the final layout of this thesis. I also wish to thank Dr Ahmed Khater of the Institute of Groundwater Resources, Egypt, for his support and valuable advice during the preparation for this research.

I am deeply indebted to those individuals, public and commercial establishments, farmers, and industrial firms who have shown willingness to answer the questionnaires, and to those who participated at the piloting stage and contributed their invaluable feedback. I would also like to acknowledge all those who granted me access to various types of data and information. In particular, I am thankful to Dr Abdulmajeed Al-Awadhi, Muneer Hajaj, and A. Jose of the Ministry of Electricity and Water, Khalid Yousif, formerly with the same ministry, Yousif Foulad, formerly meteorologist at the Meteorological Affairs Department, and Amal Al-Aradi of the Drainage and Sewerage Department. I am also very grateful to the Geological Society of London, Springer-Verlag Wein, and the Ministry of Water and Electricity of the Kingdom of Saudi Arabia for granting me written permission to reproduce figures from their copyrighted materials.

The author extends his deepest gratitude to Dr Nabeel Shams of the Bahrain Centre for Studies and Research for his helpful comments on the questionnaire designs and his input in improving the preliminary coding. Sincere thanks are due to Professor Fawzia Al-Ruwaieh of Kuwait University for arranging to carry out the chemical speciation analyses at the Kuwait University facilities. Professor Fawzia also read an earlier draft of Chapter Four and provided supportive comments. My colleague at the Water Resources Directorate, Ali Al-Shaabani offered computer expertise during the early preparation of the hydrogeological and hydrochemical contour maps. He deserves my sincere thanks.

For various aspects relating to Chapters Seven and Eight of this thesis, I have benefited from numerous direct and e-mail discussions and exchange of ideas with colleagues and experts from various institutions. I am truly grateful to Dr Ziad Mimi of Birzeit University, Palestine, Dr Nabeel Shams, Dr Jassim Al-Ajmi and Dr Mariam Al-Manaei of the University of Bahrain, Professor Omar Abu-Rizaiza of King Abdulaziz University, Saudi Arabia, Dr Hmida Klai of the Bahrain Centre for Studies and Research, Professor Ben Dziegielewski of Southern Illinois University, USA, and to Dr Ahmed Al-Yushaa of the Royal Court. Thanks must also go to Professor Abu-Rizaiza for commenting on those chapters.

My personal gratitude is due to my friends who have provided me with moral support and continuing encouragement, and stood with me during difficult times. Most importantly, I extend my most sincere thanks and deep appreciation to my family, my wife Iman and my sons Bader and Fares, who have been patient and tolerant during these taxing years. They showed genuine understanding of my pre-occupation and long absence, and provided me with the needed love and support to accomplish this research. I partially dedicate this thesis to them.

AUTHOR'S DECLARATION

I hereby declare that the work submitted in partial fulfilment of the requirements for the Degree of Doctor Philosophy under the title "Development of Water Resources in Bahrain: A Combined Approach of Supply-Demand Analysis" is the true result of my own independent original research. All authors and works consulted are acknowledged and referred to in full. All those who have helped in particular aspects are also acknowledged. No part of this work has been accepted in substance for any other degree nor is it being currently submitted for candidature for any degree.

During the course of this research, the following materials have been published and the following conferences have been attended.

Publications

1. Groundwater Management Policy in the State of Bahrain, 1999, A document Submitted to the Water Research Committee, Bahrain Centre for Studies and Research (in Arabic).

2. Water Resources in the Arab World and their Uses, 2000, Paper Presented by the Minister of Works and Agriculture at the Eighth International Conference on the Water Security in the Arab World, Centre of Arabian and European Studies, Cairo 21 - 23 February 2000 (in Arabic).

3. Water Resources in Bahrain: A List of Literature on Water Resources and Related Aspects (Compilation), 2000, A Source Document Compiled and Submitted to the Bahrain Centre for Studies and Research, Kingdom of Bahrain.

4. Water Resources in Bahrain: An Annotated Bibliography 1924 - 2002, 2003, Bahrain Centre for Studies and Research, Kingdom of Bahrain.

Copies of the publications written in English are attached with this thesis.

Conferences Attended and Participations

1. The Seventh Meeting of the Permanent Arabian Committee for the International Hydrological Programme (IHP), Rabat, Morocco 8 - 12 September 1997; presented a Country Paper on the Water Resources in Bahrain.

2. Technical Meeting on the Evaluation of Report on Groundwater Resources in the Palaeogene Aquifers in the ESCWA Region, United Nations Economic and Social Commission for Western Asia (ESCWA), Beirut, Lebanon 14 - 15 December 1998.

3. The Fourth Gulf Water Conference: Water in the Gulf, Challenges of the 21st Century, Water Science and Technology Association (WSTA), State of Bahrain 13 - 17 February 1999; co-chaired a session.

4. The Joint Kingdom of Saudi Arabia - Japan Symposium "New Attempt at Improvement and Rehabilitation of the Desert Environment", Centre for Environment and Water, Research Institute, King Fahad University of Petroleum and Minerals and Japan Cooperation Centre, Petroleum (JCCP), Dhahran, Saudi Arabia, 27 - 28 January 2002.

5. The International Conference on Water Resources Management in Arid Regions, Kuwait Institute for Scientific Research (KISR), State of Kuwait 23 - 27 March 2002.

6. The Joint Kingdom of Bahrain - Japan Symposium: Challenges on New Horizon - Towards Managing the Global Environment and Water Resources, Bahrain Centre for Studies and Research (BCSR) and Japan Co-operation Centre, Petroleum (JCCP), Manama, Kingdom of Bahrain, January 18 - 20, 2004.

Signed ....

Date 25 | 12 | 2004

INTRODUCTION

Bahrain is an archipelago consisting of 33 low-lying islands situated on the south-western coast of the Arabian Gulf at approximately latitude 25° 32′ and 26° 20′ North, and longitude 50° 20′ and 50° 50′ East, about halfway between Saudi Arabia in the west and the Qatar Peninsula in the east. These islands occur in two unequal-sized group; namely, the Bahrain Islands and Huwar Islands groups, with an area of 710.9 km^2 and a population of 650,604 inhabitants (CSO, 2002).

Bahrain is classified as an arid to semi-arid region. Its climate is characterised by low rainfall, high relative humidity, high temperature, relatively low evaporation rates, and the domination of the north-westerly winds. Rainfall is erratic and variable, and it mainly occurs in the form of short duration rainstorms, with an annual average of 78 mm. The monthly means of potential evaporation vary from 89 mm in January to 280 mm in June, with a daily average of about 5.75 mm. Relative humidity ranges from 74% in January to 59% in May and June, and averages at 66%. Temperatures are high, with monthly means ranging from 17.2°C in January to 34.2°C in July and August. Mean monthly sunshine hours range from 7.3 to 11.3 hours per day in January and June, respectively. Prevailing winds are of northwest direction, with a mean daily wind speed of about 9.5 knots. The calculated average atmospheric pressure is 1,009.8 hectapascal (hpa); but this includes ranges from 997.6 hpa in July to 1,018.7 hpa in January.

Bahrain is a flat area in which altitude ranges from slightly above mean sea level in the coastal areas to about 122.4 m in the central part of the main island; the average altitude is about 20 m above mean sea level. Physiographically, the study area can be divided into four regions, namely: the coastal plains, the multiple escarpment zones and backslopes, the interior basin and jabals, and the sabkhah lowlands.

Bahrain is a surface expression of an approximately 30 × 10 km, elongated, slightly asymmetrical north-south trending anticline known as the Bahrain Dome. This dome is one of several north-south trending anticlinal structures that represent the major oil fields in the Arabian Peninsula. It is a periclinal structure developed in the Tertiary carbonate sediments of the Lower - Middle Eocene. The core of the dome is formed by the carbonate deposits of the Lower Eocene (Rus Formation - Ypersian), which represent the oldest rocks outcropping in the country. The crest of the Bahrain Dome was eroded during the Late Eocene - Oligocene period to form inward facing escarpments of carbonate - shale units belonging to the Middle Eocene (Dammam Formation - Lutetian).

Various minor shallow seated flexures are imposed on this dome and are generally regarded as due to slumping consequent upon the removal and solution of the anhydrite from the Lower Eocene - Rus Formation (Wright, 1967). In the northern part of the main island near the Hamala area, reversal of the regional dip is noticeable at the surface along an east-facing escarpment of north - south trend. In the sub-surface, this scarp is shown to be coincident with a shallow seated monoclinal flexure or a shallow fault, possibly associated with slumping or fault movement caused by dissolution of the evaporites (gypsum and anhydrite) from the Rus Formation (GDC, 1980b).

The Lower and Middle Eocene carbonate rocks are the dominant rock types in the study area, and are predominantly limestones and dolomitic limestones with subsidiary chalky limestones and argillaceous deposits of marls and shales. Depositional environment associated with these sediments include lagoon and shallow to normal marine environments. The Miocene - Pliocene time marks the transition to more likely shoreline clastic deposition, which produced flat-lying arenaceous sediments of calcareous sandstones or sandy limestones, mainly along the peripheral islands, and coral limestone cap rock near the core of the main dome. The coastal areas are covered by shell-rich limestone and calcarenite facies, unconsolidated quartz sands, and sabkhah deposits, forming prominent raised beaches, extensive sabkhah flats, sand sheets, and dunes of Pleistocene - Recent age, typical of deposition under shoreline and aeolian conditions. Such depositional environments prevail in the area up to the present time.

Bahrain depends primarily on groundwater as the only renewable natural source to meet its water demands. The configuration of the catchments area and the prevailing arid climatic conditions preclude any surface water resources in the country (GDC, 1980b; Khater *et al.*, 1991). The aquifer systems in the study area are primarily developed in the Tertiary (Paleocene - Middle Eocene) carbonates rocks that are considered part of the Eastern Arabian Aquifer System; a regional aquifer system that runs from central Saudi Arabia to the Arabian Gulf waters, where Bahrain is located, and regarded as its major discharge basin (GDC, 1980b; Zubari,. 1987). The Tertiary aquifer systems of Bahrain crop out to the west in Saudi Arabia to receive meteoric recharge, implying that the groundwater flow regime has a north-west to south-east direction under an eastward dipping hydraulic gradient. Local recharge is minimal and only occurs at the interior basin area where the Lower - Eocene crops out and, to a lesser extent, at the surface exposures of the Middle - Eocene aquifers in the western area.

The Tertiary aquifer system in the study area consists of two aquifers: the Dammam referred to hereinafter as the Rus - Umm Er Radhuma aquifer). The Dammam aquifer is the principal aquifer and is developed in the limestone/dolomite rocks of the Middle Eocene - Dammam Formation. It consists of two aquifer units termed the Alat Limestone and Khobar limestone/dolomite aquifers. The Alat Limestone is a secondary aquifer, with an average transmissivity of about 350 m^2 day^{-1}, and a permeability averaging at 14 m day^{-1} (GDC, 1980b). The Khobar is the major source of groundwater, providing the country with more than 75% of its groundwater supply. It has an average transmissivity of about 6,000 m^2 day^{-1}, and a mean permeability value of 314 m day^{-1}.

The Rus - Umm Er Radhuma aquifer is less important, and is developed in the chalky limestone/dolomitic limestone of the Rus Formation - Lower Eocene and the dolomitic limestone/calcarenite rocks of the Upper Umm Er Radhuma Formation - Palaeocene - Lower Eocene (Montian? - Thanetian). This aquifer system occurs virtually under the whole study area in the form of a large lens, with an average transmissivity of 14,000 m^2 day^{-1}, and a mean permeability value in the region of 25 m day^{-1} (GDC, 1980b; 1983a).

Groundwater salinity in the Dammam aquifers increases in the direction of the regional groundwater flow. The Alat Limestone aquifer has a normal salinity level of between 2,400 - 4,800 milligrammes per litre (mg l^{-1}) as total dissolved solids (TDS). The Khobar aquifer contains water of a normal TDS concentration of between 2,200 - 4,500 mg l^{-1}. The salinity distribution within this aquifer is, however, extremely complicated by locally high salinity values attributed to the upward migration of saline water from the deeper Rus - Umm Er Radhuma aquifer. Groundwater in the Rus - Umm Er Radhuma aquifer has a normal TDS distribution of between 7,000 - 15,000 mg l^{-1}, coupled with a marked presence of hydrogen sulphide. In both the Dammam and Rus - Umm Er Radhuma aquifers, groundwater is of a sodium-chloride type, and has a predominant cation sequence of $Na^+ > Ca^{2+} > Mg^{2+}$, and a predominant anion sequence of $Cl^- > SO_4^{2-} > HCO_3^-$, indicating old brackish groundwater typical of a discharge area.

It follows from the foregoing discussion that even the country's best groundwater quality obtained from the Dammam aquifers is unfit for potable purposes and of marginal quality for irrigation. This water is also considered hazardous to plant growth, having an average Sodium Adsorption Ratio (SAR) of 12, and excessive chloride levels. Only the salt-tolerant crops, with specific and careful on-farm management, can survive when irrigated with such water. The high salinity of the Rus - Umm Er Radhuma groundwater, and the presence of high levels of hydrogen sulphide, renders it unsuitable for conventional direct use, except for some industrial uses. As a result, it has been primarily used for feeding desalination units with their raw water.

Statement of the Problem

Rapidly increasing urbanisation, extensive economic and social developments, rapid population growth, improved standards of living, and the influx of a large number of expatriates during the last four decades have substantially increased the demand for water, causing over-exploitation from the already scarce renewable groundwater resources far beyond their safe yield. Groundwater withdrawal from the Dammam aquifers for municipal, agricultural, and industrial uses has increased significantly from about 63.2 million cubic metres (Mm^3) in 1952 to about 187.7 Mm^3 in 2001, an increase of almost twofold. This has resulted in serious reduction of the piezometric levels and a severe deterioration in groundwater quality. Results from the present investigation indicated that almost 70% of the groundwater of usable quality has been either depleted or lost to salinisation, thus leading to soil and land degradation and abandonment of most of the cultivated land. Yet, agriculture remains the largest user of the renewable groundwater resources, generally accounting for more than 70% of the total abstraction from these resources.

The per capita water availability from the renewable groundwater resources dropped considerably from 220.5 m^3 per capita per year in 1991 to 172.2 m^3 per capita per year in 2001 (below 500 m^3 per capita per year is considered to be an absolute scarcity in the semi-arid countries (Falkenmark and Lindh (1993)). This is expected to further decrease to 136.8 m^3 per capita per year by the year 2010, if the current rate of groundwater withdrawal is continued. Water use per capita (including system leakage) increased from 91.3 gallons per capita per day (gpcd), or 414.5 litres per capita per day (lpcd), in 1981 to 113.9 gpcd (517.1 lpcd) in 2001, corresponding to an increase of approximately 25%.

The Government of Bahrain has responded to this acute water situation in two ways: (i) by augmenting the supply capacity through a phased construction of desalination and wastewater treatment plants to provide additional water supplies, and (ii) by adopting various demand management measures to conserve the existing water supplies. The emphasis, however, has been placed on the supply augmentation policy. Considerations of efficiency in water use and the effect of other demand management regulatory instruments have always been given a secondary importance.

Up to 1975, water use in the study area was almost exclusively met by groundwater resources. Since then, millions of dinars have been invested in the development of extensive desalination and treatment facilities, and water supply and treated wastewater distribution networks to provide water of high quality standards for drinking and irrigation purposes. For example, as stated in Abdullgaffar (1999), the total capital investments in wastewater treatment during the period from 1977 to 1993 amounted to Bahraini Dinar (BD) 223 million or US$ 588.7 million (1 BD ≅ 2.64 US$). A total of BD 30 million (US$ 79.2 million) is allocated for the treatment work currently being carried out under the Phase II expansion of this project. In 1984, the government spent about BD 42 millions (US$ 110.9 millions) for the construction of the Ras Abu-Jarjur Reverse Osmosis Desalination Plant (MEW, undated).

Furthermore, throughout the period 1989 – 1997, about BD 123.9 million (US$ 327.1 millions), or 17% of the total public expenditure in the 1999 fiscal year, was devoted to investment in the water sector (Abdullgaffar, 1999). Additional public water investment of about BD 13.1 million (US$ 34.6 million) is allocated for the transmission, storage, and pumping works, and other support facilities associated with the Alba Coke Calcining Desalination Plant. Another BD 10 million (US$ 26.4 millions) will be invested between 2004 and 2006 for expanding the desalination capacity of the Ras Abu-Jarjur Reverse Osmosis Desalination Plant. Planned investment in water supply installations and desalination facilities is expected to increase substantially with the development of Phase II of the Hidd Power and Desalination Plant.

While it is true that these resources have significantly contributed to alleviating the stress on the available groundwater resources, the large capital investments needed for their provision render them costly substitutes. For example, the total cost of producing, transmitting, and distributing one unit of desalinated water at the subsidised energy price is estimated at 0.370/m^3 - US$ 0.98/m^3 (Al-Mansour, 1999), compared to an average unit cost of about BD 0.020/m^3, or US$ 0.05/m^3 for the irrigation water from wells as calculated by the FAO (2002). The average unit cost of tertiary treated wastewater reaching the end-user is estimated at BD 0.046/m^3, equivalent to US$ 0.12/m^3, for the 1997 output level, and at BD 0.045/m^3 for the anticipated output level for year 2010 (PES, 1995). The average cost of delivering one unit of both desalinated water and treated wastewater is increasingly rising, imposing a heavy burden on the country's financial resources.

It must be emphasised here that, while the country's economic base during the 1980s and 1990s allowed continuous investment in expanding the water supply facilities, the current economic situation associated with the drastic drop in oil revenues, as well as the significant reduction in the country's oil reserve, suggest that such an investment practice can no longer be afforded. Indeed, developing additional expensive non-conventional water supplies represents one of the major challenges confronting the water resources planners. Privatisation of municipal water supplies and services is considered to be a potential economic solution to reduce the financial burdens associated with such costly water supply installations. The Alba Coke Calcining Desalination Plant, for example, is a BOO (Build-Own-Operate) concession governed by a water purchase agreement between the Government of Bahrain and the Bahrain Aluminium Company. Meanwhile, the government is also exploring the possibility of privatising Phase II of the Hidd Power and Desalination Plant.

In 2001, abstraction from the Dammam aquifers amounted to 187.7 Mm^3, or about 75.7 Mm^3 more than their total annual inflows (estimated at 112 Mm^3), indicating a groundwater deficit of nearly 68%. More recent data on groundwater withdrawal suggest that demand for groundwater is likely to increase significantly at least up to the year 2007. The total output from the desalination plants reached about 118.7 Mm^3 in 2001, and is expected to increase to 195 Mm^3 by the year 2006, assuming full output from the Ad-Dur Desalination Plant. During the same period (2001), a total of 15.4 Mm^3 of reclaimed wastewater was used for agriculture and urban landscaping. It is projected that around 73 Mm^3 of treated sewage effluent will be available for reuse by the year 2006. However, because of the limited renewable groundwater resources, rising costs of new non-conventional supplies, and the inefficiency of the demand management measures in conserving water use, the imbalance between the projected water demands and the available water resources is expected to be intensified. Apparently, this situation will aggravate the water shortage problems in the country, thereby threatening the sustainable development of all sectors of the economy.

Water planning efforts for forecasting future water demands have relied on the traditional method of projecting the historic trends in per capita consumption and population. By ignoring the effects of the socio-economic, technological, environmental, and demographic (other than population) factors that might have influences on water demand, this demand forecasting approach normally tends to overestimate the supply requirements, misleading capital investments plus wastage and misallocations of both financial and water resources.

Further, the demand management measures employed to conserve water and limit the need for new expensive supplies, such as leakage control, metering and tariffs, groundwater legislation, water use restriction and rationing policies, and institutional re-structuring, have been rather fragmented and have failed to achieve the anticipated objectives. This situation occurs because the policy objectives of these measures, when analysed collectively, are inconsistent with the principle of sustainable water resources development and management strategies (see OECD, 1989). Secondly, most of the legislations enacted to govern the use of groundwater lack the required legislative force. Thirdly, the fragmentation and weakness in the institutional framework, particularly with respect to the lack of effective coordination mechanisms and enforcement procedures, and the absence of public participation in the decision-making process, has placed major obstacles on the establishment of well-defined short and long-term water policies.

Objectives

The objectives of this research stem from the belief that the combination of the supply-oriented approach and the various measures emphasising demand management, have proved to be ineffective in solving the water shortage problems in the study area. It is evident that the main reason for this policy failure is that the adopted supply and demand management policies have not been properly integrated and coordinated in the form of an integrated water management plan. The basic requirements for such a plan are: a comprehensive assessment of the available water resources, a systematic analysis of the water use patterns and efficiencies, and a preparation of water use forecasts for a specified time horizon (United Nations, 1976; OECD, 1989).

This research is not intended to solve the water problems in the study area by formulating the required an integrated water management plan. Instead, the intent has been to provide a comprehensive supply-demand analytical framework that could serve as a basis for establishing such a policy. More specifically, the main objectives of this research were:

- to provide a thorough diagnostic understanding of the water problem through a comprehensive assessment of the available conventional and non-conventional water resources, with emphasis on the quality, environmental, and socio-economic constraints that influence the development and utilisation of these resources.

- to analyse critically the historical trends of water use and consumption patterns, including evaluation of water use efficiencies.
- to evaluate systematically the water demand characteristics and to develop analytical water demand forecasting models for the major water use activities.

- to examine the water supply and demand relationships and to suggest alternative future development scenarios in terms of criteria that reflect a different set of policy decisions and choices affecting water use.

Methodology

In order to ascertain the above objectives, the study entailed four integrated research activities as follows:

- the available conventional and non-conventional water resources were comprehensively assessed **(the supply side)**, through a combination of field investigations, and inventory and analysis of existing information. This involved availability assessment and evaluation of the various constraints facing the development of these resources. Extensive investigation programmes, including water sampling and analysis, construction of hydrogeological and hydrochemical databases, and mapping activities were carried out to aid in the overall assessment process.

- the past and current trends in water consumption were evaluated and analysed in their sectoral context. This analysis, together with the systematic analysis of the demand characteristics from surveys data, was considered to be the **basis** for modelling and forecasting future water demands.

- survey questionnaires were designed and administered to obtain information on the various factors influencing the demand for water in the municipal, agricultural, and industrial sectors. Cross-sectional surveys were designed and conducted to gather the required information. The surveys data were subjected to a brief descriptive statistical analysis, and were then used as inputs for developing analytical water demand forecasting models (**the demand side**).

- the water supply and demand relationships were examined and water balances for a specified time span were computed. Alternative scenarios were developed against a range of possible future and policy assumptions affecting water use (**supply-demand analysis**).

Organisation of Thesis

This thesis is organised into an introduction, nine chapters, conclusions and recommendations, and five appendices. Chapter One provides a thorough review of the literature dealing with the water resources assessment, use, and management in the study area. Approaches to water demand modelling, issues raised, and methodologies adopted are also reviewed in order to set out a reasonable methodological framework for Chapter Eight. The review of literature is meant to be somewhat comprehensive, reflecting the broad scope of this research. Chapter Two presents a considerable insight into the physical conditions of the study area, including detailed description of its climatic characteristics, geomorphology and geology. The prevailing land use patterns are also discussed in an attempt to establish a possible link between the land and water uses.

Chapters Three to Five are intended to provide a comprehensive assessment of both conventional and non-conventional water resources. This is essential to present a thorough diagnostic understanding of the problem and to prepare a basic document needed for any future re-assessment efforts, considering that updating the assessment of the water resources on a continuous basis is a pre-requisite for the formulation of a water resources management strategy. The detailed coverage of the relevant physical conditions in Chapter Two also serves this purpose.

Chapter Three assesses the groundwater resources in terms of their availability and development constraints. Particular emphasis is placed on the aquifer geometry, aquifer characteristics, analysis of water level behaviour, analysis of recharge/discharge relationship, and estimation of groundwater budgets. Chapter Four discusses the hydrochemical characteristics of groundwater in the study area. The contents of this chapter include hydrochemical representation, spatial and temporal variability in water chemistry, and groundwater characterisation and chemical speciation.

The assessment of non-conventional water resources is the subject of Chapter Five of this thesis. This includes quantitative and qualitative evaluation of these resources, including the techno-economic feasibility, social, and environmental and public health constraints associated with their development. Chapter Six considers in some detail the analysis of past and current trends of water use patterns in the major water use activities. The systematic micro-component analysis of water demand characteristics is addressed in

Chapter Seven along with the methodological issues adopted for conducting the cross-sectional surveys. Chapter Eight deals with the development of water demand forecasting models for residential, municipal, agricultural, and industrial water uses. Chapter Nine briefly examines the water supply and demand relationships, including identification of future water use levels, supply sources, computation of the water balance, and the possibility of bringing supply and demand into balance through alternative future scenarios. This chapter is followed by the conclusion and recommendations of the study.

Limitations

The limitations of this research are basically inherent in the analytical modelling side. With respect to the municipal water use survey, the assumed tolerable error of 10% is undoubtedly large, which result in uncertainties inherent in using a relatively small sample size (n = 1,106) compared to the total population. This appears to limit the ability to develop more accurate water demand models. However, decreasing the desired tolerable error to 5%, for example, would raise the sample size to (n = 4,443). Collecting a sample of this size would obviously be a task beyond the budgetary and time resources made available for this research.

The rather hypothetical consumer's willingness to pay for increase in water prices was not considered in this research. The best evaluation of the price/water use relationship is desired whenever data such as before tariff is available or where different water pricing systems (in a competitive market) are applied. Both cases are not valid for the study area where an ineffective tariff structure has been imposed for the last 12 years, and water is supplied by a single water utility. Alternatively, however, an average price specification based on total bills was tested. Although the land use patterns have been briefly addressed as part of this study, the developed water demand models ignore the interdependencies between land and water uses, primarily because of data limitation on the anticipated changes on land use patterns.

In evaluating the agricultural water use, the effects of the climatic factors (i.e. potential evaporation, average annual rainfall, wind, sunshine hours, etc.) upon the quantity of water consumed for agriculture were not incorporated in the agricultural water demand models due to time and budgetary constraints. In a small area such as the area under study, however, weather variables are unlikely to vary considerably cross-sectionally (relatively uniform at a point in time - see the detailed discussion in Chapter Two).

The agricultural water demand models have also the shortcoming of not accounting for postulated explanatory variables such as crop production and agricultural inputs (fertilizers, labour, seeds, machinery, etc.). Attempts to obtain data on these variables at a later stage failed because of time and cost constraints. No consideration is given to the effects of water costs on the agricultural water demand. For one thing, there is no administered licensing system for allocation and charging for irrigation water in the study area (i.e. water is available to farmers from their own wells and the amount of water used is not paid for); for another, the plans for implementing such a licensing system for the use of TSE for irrigation are yet to be finalised.

Factors widely known to have an impact on the demand for water by industry, such as technological and overall structural changes and economic growth, were not taken into account in this discussion. Because of their anticipated complex relationships with the quantity of water used for industry, examining the effect of these variables requires specific research on modelling industrial water demand. It is believed that the low price of water does not provide any sort of incentive for industrial consumers to adopt water-saving technologies. Therefore, the potential influence of water saving schemes (other than water recycling) on industrial demand was also not addressed in this analysis. Industries obtain water from different sources with mixed supply being a common source. This, together with the assumption that water price in industry represents a very small part of the total production costs, means that the value of water is unlikely to be a significant determinant of industrial water demand. This perhaps justifies the exclusion of water price from the industrial water use analysis.

This means that water demands for the agricultural and industrial purposes have not been dealt with in a strict economic sense, where the term water demand implies that price of water is a necessary or a primary determinant.

This study has used crude criteria for estimating some components of groundwater recharge. Clearly, employing more sophisticated methods for recharge quantification is likely to increase the accuracy of the groundwater budget estimates, which will allow for better supply-demand analysis. Piezometric data for some wells cutting deep into the Umm Er Radhuma Formation were not corrected for fresh water heads. This point warrants further attention, as GDC (1980b) noticed that piezometric heads are often depressed by high salinity of the formation fluid in such wells.

Implications for Future Research

As far as the water demands modelling is concerned, this research is of an explanatory nature in that it marked the first endeavour to analyse systematically water demand characteristics in the study area, and to develop water demand forecasting models using data from cross-sectional analysis. Regardless of the above limitations, the empirical results presented here provide a clear indication that certain socio-economic, socio-demographic, physical, climatic, and technological factors do affect water uses. Inclusion of these variables in demand forecasting models is likely to result in improved projections of future water demand.

However, because this research has followed a broad approach in addressing the water situation and management problems in the study area, additional specific research in the areas of analysing and modelling water demands are needed for each water use sector to define precisely the sectoral demand relationships. It is necessary that these models be developed appropriately with improved sampling strategies, larger sample sizes if possible, and due consideration of the inclusion of more parameters to study their relative importance on water demands. Greater emphasis in these models should be put on examining the impact of price on water use with more appropriate specifications, given that price of water plays a fundamental role as a policy instrument. Further research is also required to address the interaction between land use change and water demand.

CHAPTER ONE
LITERATURE REVIEW

Interest in the geology, hydrogeology and water resources of Bahrain dates back to the early stages of the last century (see Pilgrim, 1908; Rhoades, 1928; Heim, 1924). The 1940s and 1950s marked continued interest in the water resources of Bahrain as evidenced by the vast numbers of unpublished reports chiefly prepared by the Bahrain Petroleum Company (BAPCO) geologists (e.g. Hurry, 1940; Gulmon, 1941; Steineke, 1942; Bramkamp, 1942; Godfrey, 1948; de Mestre and Hains, 1958). These reports have focused on the hydrogeological conditions of the underground aquifers, with special emphasis on water level behaviour and water quality deterioration.

Urbanisation, an increase in levels of economic and social development, the rising standard of living, rapid growth in population, and influx of a large number of expatriates during the past four decades have led to further quantitative and qualitative exhaustion of the available groundwater resources. This has marked a shift in the approach to dealing with water resources problems, in which more detailed and systematic studies on the assessment, and development and management of the water resources of the country have been produced (e.g. Wright, 1967; Italconsult, 1971; GDC, 1980; Al-Noaimi,1993).

Given the broad nature of this research, it seems more reasonable to review the literature in five sections that adequately cover its contents. It should be noted, however, that for the sake of convenience, the hydrogeological and hydrochemical aspects related to groundwater resources will be reviewed together with the non-traditional water resources under a broad heading (Water Resources Assessment). Literature related to water use and management is reviewed under separate headings. The final section of this review considers the methodological issues relating to water demand forecasting.

Geomorphology and Geology

Contrary to the geological studies, the geomorphology, physiography and landform development of Bahrain have received less attention in the literature. Geomorphological mapping activities include: a topographic map of Bahrain at a scale of 1:100,000 compiled by Italconsult (1971); a map series sheet of terrestrial superficial deposits for Bahrain main island, and terrestrial and submarine superficial deposits and bedrock exposures for western and eastern offshore areas produced at a scale of 1: 20,000 by Messrs Sandberg (1974); simplified physiographic maps compiled by the Arab League for Education, Culture and Science Organisation (ALECSO) (1975) at a scale of about 1: 250,000; and a geomorphology and superficial materials map sheet series produced by Brunsden *et al.* (1976) at scales of 1: 10,000 and 1: 50,000 for the larger group of islands, and at a scale of 1: 30,000 for the Huwar Islands group.

The earliest account of the geomorphology was produced by de Mestre and Hains (1958), whose main conclusion was that the present land surface of Bahrain has been derived from erosion of Eocene and Miocene deposits. This was followed, in 1975, by extensive topographic and geomorphic fieldwork undertaken by ALECSO. The study area, including the Huwar Islands, was divided into nine geographical regions and two morphological groups based on their relief. The extent and geomorphological characteristics of these features and regions were described in some detail.

A very detailed account on the geomorphology, geology, and pedology of the study area, coupled with extensive field surveys, was conducted by a research team from some United Kingdom universities working under the Bahrain Surface Materials Survey Project, sponsored by the (then) Ministry of Development and Engineering Services. The outcome of this survey appeared in volumes of unpublished reports submitted to the Government of Bahrain (Brunsden *et al.*, 1976), and later in 1980 in a published work (Doornkamp *et al.*, 1980). The survey involved comprehensive and systematic investigations into the geomorphological and landform development, including detailed mapping of the superficial materials, geomorphic features, and soil units. It confirmed ALESCO's postulation that despite the apparent simplicity of the Bahrain surface and the fact that over half of its surface rarely rises to more than 20 m, an extraordinary diversity of desert landforms and complexity of pluvial features combine to form complex landscape patterns. They also noted that most of the present-day landforms owe their occurrence to aeolian activities, though many of the geomorphic features reflect fluvial processes, indicating less arid conditions in the past. The study area was divided into five physiographic regions; the occurrence of which is closely controlled by geologic outcrops, lithology, and geologic structures.

Further valuable contributions to the geomorphology, physiography and land use patterns in the study area can be found elsewhere in the literature (e.g. ERCON, 1973; Brunsden *et al.*, 1979; Bridges and Burnham, 1980; Larsen, 1983; MOH and UNCHS, 1988). Larsen (1983), in particular, gave a short but significant account of the fluvial geomorphology and distribution of the wadi systems in the study area, and drew attention to the relationship between the distribution of fresh water and land use patterns.

Literature dealing with the geological aspects of the study area is abundant, possibly reflecting the importance of Bahrain as the first oil producing country in the Arabian Gulf region. Geological mapping in the study area invloves the following activities: a geological map compiled by Willis (1967) at a scale of about 1: 250,000, primarily based on the 1: 2,000,000 regional map of the Arabian Peninsula prepared by the United States Geological Survey; a geological map of Bahrain at a scale of 1: 100,000, and three geological cross sections at scales 1: 100,000 horizontal and 1: 5,000 vertical produced by Italconsult (1971); photogeological maps showing the bedrock exposures in the area at scales of 1: 20,000 and 1: 10,000 compiled by Messrs Sandberg Consulting Materials Engineers in 1974 and 1975, respectively. These activities also involve a geological map of Bahrain and neighbouring islands prepared by Dames and Moore (1974) at a scale of 1: 50,000; geological maps at scales of 1: 10,000, and 1: 50,000 compiled by the Bahrain Surface Materials Resources Team; and a geological map of Bahrain at 1: 50,000 scale, along with three geological cross sections prepared by GDC (1980).

Pilgrim (1908) prepared the earliest memoir document on the geology and stratigraphy of the Bahrain Islands. Pilgrim divided the rock of Bahrain into three units: limestones and marls of Eocene age; a milliolitic formation, probably of Pleistocene age; and sub-recent sands, coral limestones, and littoral conglomerate. He presented a short, but significant, note on the fossil assemblages of the Eocene and Miocene Formations. A more detailed contribution to the geology of Bahrain was provided by Rhoades (1928). The aim of his work was to investigate the area as a potential oil producing locality, and much of his effort was devoted to explaining the geologic structure and irregularities within the main domal structure, particularly with respect to its southern plunge and western flank.

Between 1940 and 1958, BAPCO geologists (Hurry, 1940; Gulmon, 1941; Steineke, 1942; Bramkamp, 1942; Godfrey, 1948; de Mestre and Hains, 1958) produced numerous unpublished hydrogeological reports, in most of which the stratigraphic sequence, rock outcrops, and structure of the geological formations of Bahrain were described. Steineke (1942), for instance, provided an excellent discussion on the structural growth of the Bahrain Dome, and studied in some detail the origin of the minor structural features in the Buri area. Gulmon (1941) constructed a schematic cross section that shows the slumping features at Buri - Hamala, Hajar, and south of Manama areas, whilst the configuration of the shallow structure at the north of the Bahrain offshore area (Fasht Al-Jarim) was well demonstrated by Bramkamp (1942). de Mestre and Hains (1958) devoted part of their work to discuss the initiation and growth history of the Bahrain Dome, and to outline the depositional history of the geological formations in the study area.

The regional geological work of Powers *et al.* (1966) contained references to the structural growth and the relationship between the Bahrain and Dammam Domes. The paper by Willis (1967) produced the most systematic discussion on the geology of Bahrain, with emphasis on the depositional environments, and structural aspects of the geological formations and their possible correlation with those in the Saudi Arabia mainland. Wright (1967) envisaged the minor shallow-seated flexures imposed on the main structure as slumping features resulting from removal of anhydrite from the Rus Formation by solution.

Italconsult (1971) claimed that a few limited outcrops of the Palaeocene are probable within the central basin; a supposition that was opposed by Brunsden *et al.*, (1976b) and GDC (1980b). Their work led to the identification of two sedimentary cycles; the first one running from the Upper Cretaceous to the Middle Eocene, and the second from the

Miocene to Recent. BAPCO, in 1974, studied the economic aspects of the geology of Bahrain, in which the occurrence, lithologic characters, and the depositional setting of the geological formations were briefly outlined. The subsurface geological conditions near the Bahrain Refinery site were investigated by Dames and Moore (1974) in an attempt to evaluate the possible subsurface oil contamination below this site. The study revealed valuable information on the surface outcrops of the Alat Limestone and Orange Marl Members of the Dammam Formation. Although it was chiefly concerned with the economic geology of the study area, the report furnished an informative review of all work related to the materials aspects of the geological and resources studies carried out between 1908 and 1974.

Brunsden *et al.* (1976b) conducted extensive geological investigations, in which they suggested a new stratigraphic nomenclature for the Eocene – Miocene successions of Bahrain that completely differs from that proposed by Willis (1967). Fuller discussion on the differences between these classifications is presented in section 2.4.3 of Chapter Two, and summarised in Table 2.20. GDC (1980b) showed that the subsurface extension of the low scarp which runs southwards from Saar is associated with both the easterly Khobar downthrow and loss of anhydrite in the Rus section to the east.

A further contribution relevant to the geologic structure of the area was made by Larsen (1983) who presented an excellent discussion on the structural configuration and evolution history of Bahrain and the adjacent areas, based on the interpretation of the detailed structural work of Kassler (1973). Perhaps one of Larsen's major geological achievements is his valuable analysis of joint and fracture types, orientation and distribution, particularly with respect to their possible control on the occurrence of groundwater and natural springs. Larsen also re-affirmed the Italconsult supposition that a complex normal faulting does exist in the cultivated areas of the northern coastal plain. Supporting evidence to his conclusion included a surface topography map, a surficial geology map, and a cross section passing through the northern and northeastern coastal plains. His work also contains a useful discussion on the evolution and changing sea levels and paleoenvironmental history of the Quaternary system. Deep drilling carried out by BAPCO (see, for example, Samahiji and Chaubi, 1987) allowed more systematic growth analysis of the Bahrain Dome and other similar structures in the region such as the Ghawar anticline in Saudi Arabia and the Dukhan anticline in the Qatar Peninsula.

Water Resources Assessment

There has been a wealth of hydrogeological and hydrochemical information on the study area accumulated over the last five decades or so. The geometry, subsurface geology, and aquifer/aquitard boundaries are well defined from deep structural and shallow water well drillings. Hydrogeological mapping activities include: a structural contour map on top of the Khobar aquifer, a 1970/71 piezometric and water quality contour map of the Dammam aquifers at a scale of 1: 100,000 presented by Italconsult (1971); and a series of nine structural contour maps for the Eocene aquifer and aquitard units at a scale of 1: 48,000 prepared by Messres Sandberg (1974) based on information made available from BAPCO borehole data files.

The Groundwater Development Consultants (GDC) has undertaken by far the most extensive hydrogeological mapping work for the study area. This includes a set of structural and isopachyte contour map series for the various aquifer and aquitard units at a scale of 1: 50,000; a set of piezometric and salinity distribution maps for the Khobar and

Rus - Umm Er Radhuma aquifers for 1979 at the same scale; and a Khobar - Rus Umm Er Radhuma piezometric difference map at a scale of 1: 250,000. Their mapping activities also involved three schematic hydrogeological cross sections at a horizontal scale of 1: 100,000, and a vertical scale of 1: 5,000, and regional (including the coastal belt of Saudi Arabia) observed early piezometry, transmissivity and permeability distribution contour maps for the Khobar and Rus - Umm Er Radhuma aquifers at a scale of 1: 500,000. Al-Noaimi (1993) produced TDS distribution contour maps for the Khobar aquifer for the years 1966 and 1990 at scales of 1: 50,000 and 1: 100,000, respectively. The former map was compiled based on data made available from BAPCO data files.

Much information on the aquifers and aquitards hydraulic characteristics, and water levels and quality is available from pumping and specific capacity tests, core analysis, drilling operations and systematic monitoring at various times. The earliest account of the subject is dated back to 1940, when P. Hurry of BAPCO prepared his report. Hurry was the first to recognise the "A", "B", and "C" groundwater zones, corresponding with the Alat Limestone, the Khobar aquifers of the Dammam Formation, and the Rus - Umm Er Radhuma aquifer, respectively. Gulmon (1941) described the groundwater conditions in individual areas, and presented case histories for a selected number of wells. He suggested that water levels and quality in the Dammam aquifers be monitored quarterly in a network of observation wells; a network that was initiated in the same year.

Steineke (1942) was among the earliest to remark on the difference in water levels and quality between the northern and southern parts of the study area. In his view, this difference resulted from the erosion to sea level of the Dammam strata in the southern parts, and salinisation by seawater invasion. The relatively lesser salinisation in the southwestern area is ascribed to the presence of relatively thick Neogene cover. Godfrey (1958) commented on the rapidly declining hydraulic head and the associated salinity increase in the Dammam aquifers, and drew the first regional piezometric map for Bahrain and the coastal belt of Saudi Arabia. The main feature in that map, as noted by Zubari (1987), was the presence of a high piezometric contour of about +8 metres that extends from the coastal belt to Bahrain, indicating a flow and discharge in that direction.

In 1958, de Mestre and Hains provided an interesting and detailed review of all the previous reports and memorandums on the hydrology and groundwater resources of Bahrain prior to 1958. They analysed the water level and quality trends in various regions and produced a piezometric map for the Khobar aquifer for the year 1957, together with graphical representations of typical water analyses from the Dammam and Rus Formations. This was followed, in 1965, by an updated contribution by N. J. Hamilton. Although it contained some invalid assertions concerning the recharge to the Dammam aquifers, the report included two salinity (as NaCl) maps for the Alat Limestone and Khobar aquifers of some useful historical interest.

Wright (1967) commented on the regional flow pattern and the relationship between groundwater conditions in Bahrain and the Saudi Arabia coastal area. He reproduced and remarked on the previously mentioned regional static water level map compiled by Godfrey (1958), and presented a piezometric map for the Khobar aquifer for 1966. Aquifer salinity was shown to increase with decreasing heads, with minor salinity modifications attributed to localised pressure releases. Recommendations with regard to upgrading the existing quarterly observation network in terms of the number and design of wells, and equipment to obtain more reliable water levels and quality data, were presented.

One of his main considerations was to study the salinity gradient in the Sitra/Refinery area. He elucidated that a saline wedge was developing along the southeastern coast and that salinity deterioration in the Sitra/Refinery area suggested a progressive westwards and northwards inland advancement of the seawater front with inflow occurring through the aquifer's seabed outcrop. These findings were consistent with those of BAPCO geologists, but Wright further elaborated that vertical flow from the deeper brackish formation might also be contributing. Some methods to halt or reduce the rate of the saline wedge advancement were suggested.

Attempts to provide recharge estimates to the Khobar aquifer using a simple flow net analysis failed to produce reliable results. A transmissivity value of 1,500 m^2 day^{-1}, a hydraulic gradient of 1: 4,400, an aquifer width of 19.3 km, and a 76 mm rainfall over the recharge area were assumed for this analysis. This produced a throughflow figure of about 2.4 Mm^3 $year^{-1}$, which does not correspond well with the historical natural flow and well abstraction estimates. The most likely reasons for this underestimation were errors in static heads measurements that affect both gradient and aquifer width, but another possible form of recharge, particularly vertical flow, that might contribute to this discrepancy could not be discounted (Wright, 1967).

Later studies (GDC, 1980b; Zubari, 1987) show that Wright's calculation was not definitive and that there is a much greater flow to the Dammam aquifers, clearly evidenced from the discharge history. Wright has also attempted to visualise the head change for the period 1942 – 1966 by plotting the average heads against time, and noted that there was no indication of head stabilisation, and that extrapolation of the curve to sea level resulted in an intersection of the time axis at about 1987. Italconsult (1971) presented conclusive evidence of contamination by seawater to the Dammam aquifers on the basis of a salinity contour map and Ca/Mg ratios. However, their conclusion relating to contamination by irrigation returned flow in parts of the northern area was criticised by GDC (1980b) on the basis that such supposition seemed inconclusive, considering the combined nature of the map (i.e. it represented salinity trends in both Alat and Khobar aquifers). The lumping together of Alat and Khobar piezometric data for mapping was also seriously questioned by GDC (1980b).

Italconsult presented two controversial viewpoints with regard to the occurrence and behaviour of water resources of Bahrain: the first one is related to the presumed hydraulic inter-communication between the Eocene and Cretaceous aquifer systems. The second, and most debatable viewpoint, is the so-called "Natural Depletion Concept". This concept states that analysis of the linear recession of static head data in the Eocene aquifer system seems to indicate that the lowering of groundwater levels is mostly due to uncontrollable natural discharges rather than to extraction from wells, with no sign of reaching equilibrium, indicating that the Dammam aquifer system is naturally depleting. This would imply that the creation of a more rational system of groundwater extraction through conservation to allow water levels to recover would probably not improve the groundwater problem in Bahrain in the long-term, because this recession is mainly linked to natural causes (Italconsult, 1971). As a consequence, the study concluded that groundwater levels in Bahrain would fall to sea level by the end of the twentieth century.

This view was disputed by Wright (1972; 1977) on the grounds that, although natural depletion seemed probable, indications of localised responses to abstraction were evident from the piezometric map of 1966, where a significant cone of depression was shown around the major abstraction areas.

Wright (1977) also argued against this concept on the reasoning that there were some slight indications of a possible equilibration as shown by the analysis of head hydrographs of some observation wells for the period 1942 – 1971, where re-equilibration in response to changes in discharge regime was evident. In his view, this demonstrates the significance of local wells abstraction on head levels that would effectively refute Italconsult's contention.

A contrary standpoint to this concept was also presented by GDC (1980b) who disagreed with the evidence presented in support of a naturally decaying hydraulic gradient. They further demonstrated that the rate of water level change experienced in Bahrain during the last few decades could only have been in response to recent changes in the recharge/discharge relationship resulting from development of groundwater by artificial pumpage. Moreover, groundwater salinity evidence indicated that saline groundwater invasion had taken place only as a direct result of over-pumping in particular areas; therefore, according to (GDC, 1980b) groundwater depletion and salinisation were viewed as entirely due to abstraction from wells.

Larsen (1983), too, refuted Italconsult's concept of natural depletion and added valuable support to the traditional throughflow theory. He revised Italconsult's findings regarding the depletion rate for Bahrain based on archaeological and changing sea level evidence, and concluded that their interpretation was an obvious oversimplification, and that there is no simple case for natural depletion of the Eocene aquifers since the Late Pleistocene.

The Food and Agriculture Organisation of the United Nations (FAO) completed a comprehensive survey on the shared water resources in the Gulf States and the Arabian Peninsula. The principal objectives of the study were to review all hydrogeological reports available for the area in order to provide an up-dated assessment of the system's behaviour, and to determine whether water resources are shared between these countries (FAO, 1979).

The FAO report has seriously questioned the traditional hydrogeological view that there has been a dynamic tongue of fresh water which flowed to and sustained the aquifer in Bahrain, through a regional aquifer system. Its main argument was that the existing piezometric and hydrochemical data were inconclusive to suggest a regional flow system. Instead, the report viewed the groundwater of the Eocene aquifer system in Bahrain and Saudi Arabia as local discontinuous lenses-type aquifers (termed Aquifer System B) floating on top of saline Umm Er Radhuma's groundwater, sustained by recent meteoric recharge. This would mean that abstraction from the Umm Er Radhuma aquifer in Saudi Arabia could only disturb the interface between the fresh water lens and the saline Umm Er Radhuma water, and that the possibility that such an interface would spread to Bahrain needed to be further investigated. Supportive evidence for this argument included hydrochemical and isotopic data, and a simple flow net exercise that envisaged an unconfined aquifer lens condition, and it was further asserted that although these data were insufficient to produce conclusive evidence, they demonstrated a probable lens-type aquifer.

In his comments on the report findings of FAO (1979), Wright opposed this theory by stating that although the occurrence of local recharge into the aquifers in Bahrain was well documented, most apparently in the central basin into the Rus and in localised areas in the northern part into the unconfined Dammam, a great deal of work was required to further examine the FAO's contention, and that the rates of the recent recharge and accumulated storage were unlikely to be sufficient to support the lens-type aquifer theory. Further, he questioned the isotopic chemistry evidence presented by the FAO and the validity of their calculations regarding the probable pumping history of the presumed aquifer lens, particularly with respect to the application of the northern coast data to the whole of Bahrain. He pointed out to some inconsistent features that contradicted this theory and concluded that water levels and chemistry appeared more consistent with normal throughflow conditions from the Saudi Arabia mainland.

The FAO's theory was also rejected by GDC (1980b) who affirmed that such a hypothesis was merely based on indirect and somewhat dubious geophysics and isotopic evidence, while it ignored the direct piezometric evidence of a regional flow system. They also considered the occurrence of tritium in water samples from all the aquifers in Bahrain analysed by Italconsult and used to support the FAO's concept, to be quite inconsistent with the generally accepted throughflow theory, and simply viewed this occurrence as possible sample contamination. Their main contention was that, although recharge by recent rainfall exists in parts of Bahrain, freshwater in the Dammam aquifers in Bahrain are derived from regional throughflow and then upward leakance from the Umm Er Radhuma Formation, suggesting that such a system does involve sharing, and abstraction from Saudi Arabia does affect Bahrain. The degree of the hydrogeological interdependence between the two countries was further investigated by the use of groundwater mathematical models (e.g. GDC, 1980b; Zubari, 1987).

In 1980, GDC completed detailed hydrogeological and hydrochemical investigations, including aquifer testing and sampling for both the Khobar and Rus - Umm Er Radhuma aquifers, well inventory, and construction of regional groundwater models for Bahrain and the coastal belt of Saudi Arabia. This has provided substantial insight on the aquifer system's behaviour and geometry, aquifer parameters, groundwater chemistry, isotope analysis, and recharge/discharge quantification. Their hydrochemical investigations reveal that the Dammam aquifers in Bahrain receive relatively low salinity throughflow water from Saudi Arabia, but this is salinised around the eastern coast as water travels down the flow path, and in the north central part because of contribution from seawater invasion and upconing of saline water, respectively. An advancement rate of saline front to the Dammam was estimated at between 60 to 139 m year^{-1}, and the vertical upflow rate was estimated using a computer simulation model. Isotopic dating using tritium proved the probable recent meteoric recharge at Bahrain core, and initial isotope measurements using radiocarbon methods suggest that the age of Bahrain's throughflow groundwater ranges between 6,000 to 22,000 years.

Wright *et al.* (1983) published a brief but useful account of the hydrogeology and hydrochemistry of the study area. The investigators paid considerable attention to the controversial points regarding the origin of Bahrain's relatively fresh groundwater, particularly the one related to the lens theory versus the traditional throughflow concept. In their view, the generally accepted lateral throughflow concept is more reasonable to describe the hydrodynamics of the Dammam aquifer system in the area. As they put it " .... development of the aquifer systems in coastal Saudi Arabia and Bahrain has had, and will continue to have, mutual repercussions".

In 1983, the Rus - Umm Er Radhuma aquifer was evaluated by GDC as a potential water source for a proposed reverse osmosis desalination plant. The effects of the proposed large-scale development on the Bahrain's overall groundwater was investigated, both in terms of quality and quantity. The results of the computer simulation models suggested that the aquifer could be viewed as a limited, non-renewable lens-type aquifer of brackish water of a salinity of between 8,000 - 15,000 mg l^{-1} TDS. It has been concluded that development of this aquifer to feed the proposed 46,500 m^3 day^{-1} reverse osmosis plant is feasible. However, since this lens is of limited lateral extent, with this continued large abstraction, the aquifer salinity would eventually reach that of the sea water or even worse; long-term monitoring of the system behaviour and periodic updates of the models to investigate its future response to this abstraction was therefore recommended.

The more recent work by Zubari (1994) up-dated and recalibrated the multi-layered mixing cell strip models developed by GDC. This embraced a transient-condition calibration based on the observed transient data accumulated from 1984 - 1993, which were checked against the initial forecasts made by GDC. Analysis of the aquifer piezometry and salinity changes indicated that a uniform depletion of the brackish water lens was taking place, though no major variations in the total dissolved solid concentration of the produced water within the intervening period was observed. Zubari's main conclusion was that there was an upward movement of the mixing zone of more than 15,000 mg l^{-1} of dissolved solids into the brackish water zone, indicating that the salinity of the produced water might show an increase over the coming years.

An extensive assessment of the water resources of Bahrain was carried out by Al-Noaimi (1993). The spatial and temporal variation trends in total dissolved solids, and water level changes were discussed. The results of this investigation re-affirmed the critical position of groundwater resources in Bahrain. Al-Noaimi (1993) also analysed the recharge/discharge components for the Dammam - Neogene aquifer system and was able to prepare a groundwater budget for this aquifer system for the year 1990, which showed an imbalance of 96 Mm^3 of outflows over inflows.

In general, the assessment of non-conventional water resources has received less attention in the literature of the study area, although the Associated Consultant Engineers (ACE) have evaluated the TSE as a potential and viable source for re-use for irrigation in a series of reports (see, for example ACE, 1984; 1989; ACE-Al-Moayed, 1997). Al-Noaimi (1993), however, provided a comprehensive assessment of the non-conventional water resources, encompassing desalinated water, TSE, and agricultural drainage water, with emphasis laid on the quantitative and qualitative aspects of these resources, including the economical, environmental, and technical constraints facing their development.

Water Use and Management

Literature dealing with historical trends of water use patterns in the study area is abundant. This normally includes time series data on discharge from springs, abstraction from wells, and estimates of non-traditional water resources utilisation. Heim (1924) presented the earliest estimates on the water use in the study area, where he identified 16 land springs, discharging about 57 Mm^3. This survey was considered incomplete, and Heim's figure was later reviewed by several researchers. BAPCO launched a comprehensive programme aimed at measuring discharge from the land and offshore springs, and abstraction from wells. As part of this programme, Ferguson and Hill (1953) surveyed the land springs and found that only 47 out of the 153 springs surveyed were flowing, with a total flow of about 42 Mm^3 $year^{-1}$. This was followed by an offshore spring survey made by Hill in 1953, in which 20 sources were identified, discharging about 9.6 Mm^3 $year^{-1}$. In both the land and offshore spring surveys, discharge estimates were made based on measured flow.

Abstraction from wells began in 1925, and accelerated through the 1940s and 1950s. The first artesian well survey was conducted in 1953 by Porritt, who inventoried some 311 water wells, with an estimated total abstraction of 64 Mm^3 $year^{-1}$ (Porritt, 1953). These estimates were based on metered abstraction, with only a few wells being indirectly estimated. Abstractions from shallow hand-dug wells were omitted. This abstraction figure was considered very high, and must reflect high application rates in agriculture (calculated at about 5m per year). As described by Porritt (1953), this application rate is well in excess of the average irrigation demand plus leaching requirements, and implies a considerable waste of irrigation water.

In 1967, Sutcliffe studied the abstraction history in the study area, and estimated the total discharge for the year 1966 at about 153.2 Mm^3, of which 115.6 Mm^3 was withdrawn from groundwater. Sutcliffe noted a progressive decline in total spring flows to about 37.6 Mm^3, of which 28 Mm^3 were from the land springs and 9.6 Mm^3 from the offshore springs. The municipal and BAPCO abstractions were obtained from the authorities concerned, and the irrigation uses were estimated indirectly on the basis of the total consumptive use, plus a 25 to 50 % allowance for leaching requirements. The areas of the irrigated land were identified from the 1964 air photomosaic and the climatic data were obtained from the Muharraq and Budaiya meteorological stations. Sutcliffe also re-estimated Heim's figure by assuming that the total discharge in all springs declined at a fixed linear rate as in the four major springs. Accordingly, he assumed that 70 Mm^3 was a more reasonable estimate for the incomplete 1924 survey. In order to complete the discharge picture of 1924, Sutcliffe assumed that the submarine spring flow had remained unchanged between 1924 and 1952 (i.e. at 9.6 Mm^3), implying that the total discharge in 1924 was about 79.6 Mm^3.

Italconsult (1971) presented discharge estimates for 1971. Their estimates were based on actual watering rates on selected sample farms and measured cultivated areas, with abstraction from hand-dug wells being considered. The study showed that between 1966 and 1971, the abstraction from wells increased by 11.5 Mm^3 $year^{-1}$, to a total of 127.1 Mm^3 $year^{-1}$, whilst the offshore spring flow dropped by 8.6 Mm^3 $year^{-1}$, to a total of 29 Mm^3 $year^{-1}$. Italconsult argued that the 1966 well abstraction figure estimated by Sutcliffe was an obvious overestimation resulting from a miscalculation of total irrigated land. They discovered that out of the flowing 47 springs identified during the 1953 survey, only 9 springs were then flowing at a gross rate of 7 Mm^3 $year^{-1}$.

Wright and Ayub (1973) carried out a valuable study on groundwater abstraction and irrigation in Bahrain, in which they postulated that both the 1924 and 1952 estimates were likely to be low by at least 10 %. They also opposed the Italconsult view of the past consumption level (between 250 and 300 Mm^3 $year^{-1}$ before 1924) on the basis that the 6.6 m watering rate assumed by Italconsult might be representative for farms irrigated by wells, but seemed very high for farms supplied by springs. They found, based on actual measurements, that an application rate of about 2.6 m was a more reasonable estimate.

Wright and Ayub (1973) measured the groundwater abstraction in representative selected farms with different application rates and found that the total groundwater withdrawal for 1972, including water used by abandoned date palms was about 159 Mm^3. Their findings indicated that total water use in agriculture was in excess of beneficial requirements by at least 50 Mm^3 $year^{-1}$. A follow-up investigation into consumptive use and possible metered abstraction measurements is proposed.

As part of their comprehensive well inventory and spring surveys of 1980, GDC located 1,422 water points, including 1,386 drilled and dug wells, 12 land springs and 24 offshore springs. Abstraction from wells was estimated at about 138 Mm^3 $year^{-1}$, and the land and offshore springs were reported as yielding 8.1 Mm^3 and 6.6 Mm^3 $year^{-1}$, respectively. The land and offshore spring discharge estimates were based on direct flow measurements, while well abstraction was based on actual discharge on sample wells and the number of seasonal watering hours. GDC shared Sutcliffe's view concerning the incomplete Heim survey, but suggested that a 13 Mm^3 for offshore spring discharges was a more credible estimate for 1924, assuming allowance for diffuse flow. They also took care to correct what they considered to be underestimated figures of land spring flow of Hill (1953) and Italconsult (1971), from 9.5 to 12.8 Mm^3 $year^{-1}$, and from 7 to 23 Mm^3 $year^{-1}$, respectively. In 1990, the total discharges from springs were predicted to be approximately 5 Mm^3, out of which 1.5 Mm^3 were from the land springs and 3.5 Mm^3 from the offshore springs (Al-Noaimi, 1993), against a total groundwater withdrawal of 219.3 Mm^3.

The supply/demand relationship was evaluated by Al-Noaimi (1993), who made a water budget estimate for the year 1990, basing his calculations on the analysis of the available and exploitable water resources. His water budget analysis revealed a total available resource of 245.8 Mm^3 against a utilised amount of 258.3 Mm^3. It should be noted, however, that the estimate for the available supply includes about 31 Mm^3 from potentially unusable sources (e.g. agriculture drainage water) owing to its high salinity. Al-Noaimi and Khater (1995) adopted a similar approach to produce a water-use analysis update and a water budget for the year 1993.

Froment, in 1965, published his article on the water supply of Bahrain in which he suggested that for any water conservation programme for Bahrain to be effective, it must begin with the principle of public ownership of the water resources, accompanied with a controlled licensing system for privately-owned wells. Wright (1967; 1972) and GDC (1980b) suggested an agreement with the Government of Saudi Arabia for exploitation of shared aquifers, with which a programme of bi-lateral investigation and development between the two countries could be agreed upon.

Wright (1967; 1972) noted that agriculture was consuming about 85 % of Bahrain's groundwater, and that normal irrigation practices in the study area waste large amounts of water. An irrigation and agricultural efficiency programme of studies was undertaken to ascertain the irrigation efficiency in a number of selected experimental sample farms. Fuller discussions of this programme, including methods of investigation, constraints encountered, and results obtained are contained in Wright (1972) and Wright and Ayub (1973). A communal wells scheme to substitute the numerous private irrigation wells, and a new water management organisational structure that involved establishing a Central Water Authority and Water Resources Board were envisaged as vital management options to solve the water resources problem in Bahrain.

The multi-layered three-dimensional regional flow model developed by GDC in 1980 for the Dammam Aquifer System in Bahrain and the coastal belt of Saudi Arabia, as part of the Umm Er Radhuma Study, was run in predictive mode to investigate the available management options. These predictive runs were based on the GDC's groundwater demand projections for the year 2000. Nine development options were considered to predict the system response to various abstraction regimes. It was concluded that all options that maintained or increased the current level of abstraction increase the salinisation hazard, which meant that only a major reduction in abstraction could prevent resources from further exhaustion.

The aquifer system was found to be responding rapidly to the changes in abstraction regime, and that throughflow to Bahrain could only be preserved by cutting abstraction from the Dammam aquifer to the level that would raise the piezometric head in the northwestern coast by at least 1.0 m. This could not be achieved unless the total annual abstraction from the Dammam is reduced to 90 Mm^3, the figure that represents the annual throughflow from Saudi Arabia mainland and considered to be the groundwater safe yield, and the abstraction in the coastal Saudi Arabia is kept at its 1979 level. These management recommendations led to the enactment of the Amiri Decree No. 12/1980 (a legislation that governs the use of undergroundwater), and the creation of the Supreme Council for Water Resources in 1982 with the main duty of setting up the country's overall water policy.

Considering that agriculture is the major consumer of groundwater, the Government of Bahrain has adopted a five-year plan (Agricultural Development Plan 1981 – 1986) (MOCA, 1980), aimed at reducing groundwater abstraction for irrigation and to enhance its efficient use, mainly through the introduction of modern irrigation techniques, provision of agricultural advisory and extension services, and the use of treated sewage effluent in irrigation. Although the plan accomplished some of its objectives, there has been, as described earlier, an increasing trend in groundwater withdrawal, particularly for agriculture purposes, indicating that further water management efforts are still required.

The idea of communal wells was, once again, proposed as part of the Central Irrigation Project. The aim of this project was to define management strategies to reduce abstraction from the Dammam aquifer and secure its long term availability, while at the same time optimising agricultural productivity by re-using TSE for irrigation (RMI, 1984). The consultants suggested three groundwater management alternatives. These included: a centralised supply and distribution scheme; an individual bore management scheme that embraces metering and licensing, supported by charging policy for excess water use; and a composite water management scheme that combines the first two alternatives, with a centralised system to be confined to the zones of higher abstraction. Despite the fact that the composite option was favoured over the other options because of its relative social, political, economic, and technical viability, it was not implemented. Instead, individual bore management scheme was adopted in the mid-1980s, but unfortunately without a licensing system or imposition of charges for excess water usage.

Khater *et al.* (1991) suggested a planning framework for the development of water resources in Bahrain, stating that water use analysis based on the most probable future conditions, water saving measures, public awareness, and alternative sources of water were key issues in the planning for the development of such limited water supplies.

In view of the increasing cost of providing domestic water because of the introduction of a desalinated supply, water demand management has become a necessity. Measures that have been adopted to control the demand for domestic water involve leak detection, distribution network rehabilitation, metering and pricing mechanisms, a consumption ceiling policy, and educational campaigns on water saving (see for example Al-Mansour, 1992; Qamber, 2001; Al-Maskati, 2001). As disclosed by Al-Mansour (1992), these measures have contributed significantly to restraining the domestic water demand. The enhancement of the institutional arrangements was also considered essential for legislation enforcement and improvement of the institutional functions within the water sector (Al-Noaimi, 1993).

Previous works on the water management in Bahrain include an attempt by Khater (1994a) to re-allocate the water resources based on actual water requirements, taking into account the country's limited resources. He stressed the need for an urgent groundwater management programme in order to prevent the otherwise inevitable total loss of the remaining relatively fresh Dammam aquifers groundwater. By implementing such a programme, the author argued, a gradual reduction in groundwater abstraction of about 100 Mm^3 is anticipated by the year 1997, out of which 66 % represents the expected gain in the agricultural sector and 34 % in the domestic sector.

Water Demand Forecasting

GDC (1980b) produced a groundwater demand projection for the Dammam aquifers for the year 2000 based on a simple extrapolation of historical trends. This represents the earliest work on the projection of groundwater demand. The results indicated that a total of 167 Mm^3 would be required to meet the overall demand by the year 2000, assuming that an additional amount of about 23.4 Mm^3 of desalinated water, plus what was then available (8 Mm^3) would be available for municipal consumption starting from the year 1985. No allowance was made for a possible increase in the desalination output beyond this year. The projection also showed that if the desalination capacity remained at 8 Mm^3 $year^{-1}$, the gross groundwater demand would reach 193 Mm^3 by the end of the projection period. While both the municipal and industrial demands were projected to continue increasing, the consultant assumed that the improvements in irrigation practices would reduce agriculture demand by 10 Mm^3. The probable contribution of TSE in meeting part of the agricultural demand was not considered in this projection. The spring flows were projected to decline to 5 Mm^3 in the year 2000, in line with the decline rate observed since 1924.

The average daily per capita consumption, with the peak summer demand to the average annual daily demand ratio (peak factor) being taken at 1.25 was used to estimate the municipal water demand for the year 1985 (MWPW, 1979). The per capita averages were calculated at 318 and 272 lpcd, or 70 and 60 gpcd for the urban and rural areas, respectively. The demand was projected as a direct product of the gross per capita and the low population projection, which envisaged stabilisation of the Non-Bahraini population at its 1978 level, and an annual increase in the Bahraini population by 3.2 % from 1978 to 1985. Allowances had been made where appropriate to cater for the water requirements of the existing and foreseeable industrial and commercial developments. The generated average municipal demand for the year 1985 totalled about 50 Mm^3, and was projected to increase to 62.4 Mm^3 during the summer peak.

In 1981, these estimates were reviewed and updated, and were extended up to the year

2000 (MWPW, 1981). The water demand here was also treated as a simple linear function of the per capita municipal water use and the population growth over the projection period. The results showed that the projected total municipal demand is expected to reach 79.6 and 142.7 Mm^3 for the years 1985 and 2000, respectively. This included the industrial demand, which accounted for 14.2 % (11.3 Mm^3) and 11.6 % (16.6 Mm^3) of the total municipal demand, respectively, for the years 1985 and 2000. It should be noted here that although the report made some assumptions regarding socio-economic and demographic factors that might have some influence on the water consumption, the effect of these factors on the projected demand was not quantified. Perhaps this was to allow some flexibility to the projection through theoretical but rather implicit assumptions.

It is more likely that the assumed per capita daily consumption rates were not derived from historical-trend values; alternatively, they were considered reasonable only if the planned conservation campaign and the leak detection programmes were successfully implemented. In fact, the per capita consumption in some areas such as Manama and Isa Town was by then as high as 477 lpcd (105 gpcd). The municipal water demand was re-estimated through the year 2001 based on the historical water use patterns, taking the peak daily demand as the projection criterion (MWPW, 1988). The projection showed that demand would continue to increase by about 64.7 % from the base year level of 106.8 Mm^3 to 175.9 Mm^3 in the year 2000. When compared with the 1981 projection results, these demand figures were, apparently, very high and did not reflect the actual municipal demand. It appears that the peak daily demand criterion was adopted only to emphasise the critical water supply situation witnessed during the late 1980s. As possible explanation, it appears that the over-enthusiasm by the planners to promote their case led them to over-estimate the demand. Such a tendency can always be expected in countries faced with severe water problems.

Al-Noaimi (1988; 1989) provided a groundwater demand projection for agricultural and industrial water uses for the year 2000. This projection was based on the historical trend in groundwater abstraction, growth/decline in agricultural land, and the planned industrial developments. These were supported by some assumptions, including the contribution of TSE and possible control of the new groundwater regulations on the abstraction patterns. The total municipal demand resulting from the MWPW (1988) projection, less the projected desalination capacity, was considered reasonable to represent the groundwater municipal demand. According to Al-Noaimi (1988), the irrigation demand was projected to continue increasing to a maximum of 140 Mm^3 in 1992, but would then decrease as a result of the probable contribution of TSE, coupled with the anticipated reduction in agricultural land. Beyond this year, however, the demand for irrigation water was expected to stabilise, and to remain at nearly the same level as the base year demand towards the end of the projection period.

The annual municipal demand was projected at 102 Mm^3, assuming no additional desalination capacity above what was then available (63 Mm^3 - including output from Ad-Dur Plant) was achieved. The report anticipated that the abstraction from the Dammam aquifers to meet the industrial demand would progressively decline at the same rate as observed during the previous nine years to about 2 Mm^3. In contrast, the industrial withdrawal from the Rus - Umm Er Radhuma was projected to increase to 10.5 Mm^3 in the year 2000. This was because industrial water users were expected to switch to this aquifer to meet their demand, in response to the groundwater regulations that encourage industrial consumers to tap this aquifer, and to retain the Dammam groundwater for municipal and agriculture purposes. Consequently, the total projected groundwater demand was estimated at 264.5 Mm^3, of which 224 Mm^3 was projected to be withdrawn from the Dammam aquifers and 40.5 Mm^3 from the Rus - Umm Er Radhuma aquifer.

A water demand forecast model using the component analysis approach was employed to forecast the municipal demand up to the year 2005 (Mott McDonald, 1997). Three components were considered: legitimate consumption, unaccounted-for water, and other water uses. The key inputs to the model were the trends in per capita water use and commercial/industrial demands, population forecast, and growth in gross domestic product (GDP). The per capita municipal consumption (including commercial and industrial water uses and the unaccounted-for water) was taken at 424 lpcd (93.3 gpcd) in the base year (1996) and predicted to increase to 440 lpcd (96.8 gpcd) by the year 2005 (Mott McDonald, 1997). The previously stated peak factor of 1.25 was adopted to calculate the peak daily demand.

The total billed and unbilled commercial and industrial consumption, future planned industrial developments, and the estimated total self-supplied consumption were used to forecast the commercial and industrial demands. The unaccounted-for water from leakage was estimated to reduce from 14 % of the total water supplied in 1993 to 8.6 % in 2001 in response to the leak detection programme. No further reduction was envisaged beyond this date. The other unaccounted-for water was estimated to decrease from 1.5 % in 1993 to 1.0 % in 1996. The forecast indicated that the municipal demand in 2005 would reach 209.6 Mm^3, representing a net increase of 32.2 % over the base year demand of 158.5 Mm^3.

The above figures represented the base case forecast, where a medium population and GDP growth were envisaged. Three additional alternative forecasts were also investigated: the high forecast, low forecast, and the demand management forecast. The high forecast assumed high population and GDP growth, whereas the low forecast envisaged low population and GDP growth. The demand management forecast adapted the base-case forecast assumptions, plus making suitable allowances for implementation of certain demand management practices. The municipal water demands at the end of the projection period for the three alternative scenarios were, respectively, 231.9, 192.8 and 189.7 Mm^3.

Recently, a demand model was developed to forecast the groundwater demand for the time span 1999 - 2020 (Abdulgaffar, 1999). The demand-determining variables were chosen to be the historical trend values of groundwater abstraction and population growth. The total demand for the year 2020 was predicted to be about 549 Mm^3, indicating a net increase by around 124.1 % from the base year demand of 245 Mm^3. This prediction assumed the medium population projection. A further two alternatives were examined to represent the effects of assumed population policies on the total groundwater demand. The first scenario assumed an annual reduction in the Non-Bahraini population from 3.39 % to 1 % from 1999 to 2020, while the Bahraini population continues to grow at the same rate. The second scenario was based on the assumptions that the Non-Bahraini population would remain constant at the 1998 level up to the year 2020, and that the Bahraini population would increase normally. The groundwater demands for these alternatives for the year 2020 were projected to be 451.7 and 423.4 Mm^3, respectively.

Zubari (1999) projected water requirements for the agricultural and municipal sectors in

Bahrain for the years 2005 and 2010, with contributions from groundwater, desalinated water, and TSE being separated. The industrial sector consumption was assumed to remain at its current level (i.e. less than 10 Mm^3 $year^{-1}$). The author assumed that all available TSE would be used in irrigation, and that the annual increase in water requirements observed during the previous 10 years would also continue during the coming 10 years. Total water demand for the year 2010 was projected to reach 406 Mm^3, of which 240 Mm^3 represented the agricultural share, and 166 Mm^3 was for municipal demand.

Literature devoted to forecasting the irrigation water demand is scarce and is primarily concerned with future irrigation requirements from TSE. An estimate of the TSE irrigation water requirements was first reported by McGowen (1975) at an average of 30,000 m^3 per hectare per year (m^3/ha/year) for agriculture and 20,000 m^3/ha/year for landscape irrigation, but this was considered to be an underestimate. The utilisation of TSE began in 1985, and since then, the potential of this source to meet the irrigation demand has been widely investigated (e.g. ACE, 1984; ACE, 1989; ACE; 1990; PES, 1995; ACE, 1997). ACE (1984), for instance, suggested that about 19.7 Mm^3 of the TSE would be needed for agricultural uses in 1995. This amount was projected to increase by 85.7 % to 36.6 Mm^3 in 2010.

As part of Phase II expansion, a total irrigation demand (including landscaping requirements) for the year 2000 was estimated at 57.6 Mm^3, assuming an application rate of 70 m^3 per hectare per day (m^3/ha/day) (ACE, 1989). Later, in 1990, a separate landscape irrigation demand figure of 10.3 Mm^3 for the same projection year was presented by ACE (1990). PES (1995) produced the most detailed account on the irrigation water requirements, in which the total irrigation demand was projected to reach 80.7 Mm^3 by the 2010. Out of this figure, TSE was estimated to represent about 79.7 % or 64.3 Mm^3. Higher estimates for the same projection period were reported by ACE (1997). Evidently, such an overestimation is attributed to the increase in the assumed application rate from 70 to 90 m^3/ha/day. The generated demand for the year 2010, which was a product of the application rate and the total irrigated area, was computed at 93.7 Mm^3. This level of demand represented a net increase of 35.6 % above the year 2000 level of 69.1 Mm^3.

Methodological Framework

In broad terms, there are two approaches documented in the literature to modelling and forecasting water demands; namely, the statistical approach, and the engineering/programming approach. The statistical approach embraces two major techniques: namely, the extrapolative and analytical techniques. The former is concerned with prediction of the future value of the variable under consideration from the projection of past trends, using the so-called time-series analysis (Gardiner and Herrington, 1986). The analytical technique attempts to explore the possible functional relationships between the quantity of water demanded and other explanatory variables by infering from a set of observations on many users at a point in time, using specific methods of analysis (Gardiner and Herrington, 1986; Bower *et al.*, 1984; Kindler and Russell, 1982). The engineering approach attempts to construct a water-demand relation from fairly detailed engineering knowledge of the production or consumption unit processes, and the associated substitution possibilities carried out by the activity (Kindler and Russell, 1982), using the mathematical (usually linear) programming procedure.

The trend extrapolation method was widely used over the past decades, but is now in increasing disfavour, primarily because it is often possible to obtain very different predictions from trends which fit past data almost equally well; in addition, it is intellectually indefensible to assume, as does most extrapolation, that past trends will continue into anything more than the short-term future (OECD, 1989). The fundamental shortcoming of the trend extrapolation analysis is that it does not incorporate certain variables which might have significant effect on the forecast. For instance, Batchelor (1975), presented proofs of the failure of the extrapolative forecasts in England because of ignoring the importance of water-using appliances as demand-determinant variables. He observed that water demand is significantly influenced by variations in household technology. Power *et al.* (1981) stated that predictions of water use with the extrapolation of previous trends in per capita consumption are not able to account for changing patterns in the various factors affecting consumption. Grima (1973) and Park (1986) highlighted the importance of the policy and socio-economic variables in forecasting water demands. Archibald (1983) shared the same view, and found that trend projection normally over-estimates future demand because it cannot reflect some important demand relevant variables, such as a change in technology, and concluded that forecasts employing such methods are often likely to be highly inaccurate.

Rees and Rees (1972), examined the simple trend extrapolation forecasts of 1966, adopted by the Water Resources Board (WRB) for England and Wales, and observed that the forecasts were well above the demand levels which would be expected from the best estimate of past trends and, hence, resulted in needless excessive supply capacity installations. Rees and Rees suggested an alternative forecast that also uses the past trends in total consumption, but takes into account the effect of the weather conditions.

The forecasting equations were obtained by least squares regression, with total water consumption and per capita consumption being the dependent variables, and time and mean summer rainfall as independent variables.

The problems associated with the use of extrapolative forecasts were also investigated and seriously questioned by Herrington (1973), Kindler and Russell (1984), and Archibald (1986). For example, by assessing the 1966 forecast of the Water Resources Board, a significant overestimate of some 20% was uncovered (Herrington and Tate, 1971 reported in Batchelor, 1975). However, although Herrington (1973) believes that, in a general sense, extrapolative techniques are inferior to analytical techniques, he observed that in the case of metered industrial consumption in England and Wales, the former produced better explanations. His findings also suggested that for the metered municipal consumption in the Trent River Area, both methods yielded almost consistent results. Mitchell and Leighton (1977) presented a useful comparison of multivariate and trend extrapolation forecasts with actual water use in Canada. They postulated that both the multivariate and trend forecasting procedures provided encouragingly accurate results when compared to actual water use, though multivariate procedure showed more precision.

In a comprehensive empirical study that compared trend extrapolation with more sophisticated analytical forecasts, Makridakis *et al.*, (1982), confirm that more sophisticated methods are not necessarily more accurate than simpler ones. Dziegielewski and Boland (1989) compared the results of a per capita forecast and the IWR-MAIN forecast, and concluded that the per capita method might often capture the trend in water use but would not identify its causes. The United Nations (1976) argued that the superiority of analytical models over extrapolative techniques lay not in their greater accuracy, but in their capability of assessing the consequences of various assumptions and policy options, which is the underlying principle of the alternative scenario approach. Gardner and Herrington (1986) also believe that accuracy is not the only criterion of interest, and that the choice of method must also depend upon the type of data, type of series and time horizon of the forecast, as well as upon budgetary constraints.

Recently, however, preference in the literature has been towards the rather more sophisticated analytical techniques. Within the context of these broad analytical techniques, a number of forecasting methodologies have been proposed by various workers. Archibald (1983), for instance, suggested an approach that disaggregates the water uses into different components; in each component the demand is calculated as from its characteristics, and the total demand is made up from the sum of the component demands. The importance of such disaggregation stems from the fact that the major difficulty in forecasting water demand is its multiplicity of uses, each with a different potential rate of growth in demand. This approach has been employed to forecast the domestic and industrial water demands in England and has produced far better results than the traditional time series and multiple regression methods.

An approach similar to the disaggregated (components) approach was also developed in the United States (Power, *et al.*, 1981), and is termed the deterministic approach. This modelling approach, according to the authors, tends to divide total consumption into its components and then allows for changes which affect these components separately. The component demands are then combined to give the total predicted residential consumption. Such an approach was applied to forecast the residential water demand in Townsville, Australia, by breaking it down into a lawn water requirement and an in-house use, and proved capable of producing reliable results (Power, *et al.*, 1981).

Another demand forecasting approach that resembles the previously described components approaches in a methodological sense, but differs in its analytical technique, was developed by the Institute of Water Resources of the U.S. Army Corps of Engineers to forecast urban water demand. This approach is incorporated into a computerised forecasting model, named the IWR-MAIN model. It disaggregates the water demand into a large number of categories, each consisting of a relatively homogenous group of water uses, and then links the water use in each category to the factors that determine the need for water as well as the intensity of water use (Dziegielewski and Boland, 1989). The researchers argued that the main advantage of this model is that it takes into account several demand determinant factors, such as the price of water and wastewater discharge, household income, number of persons per household, weather and conservation factors; besides it allows for further inclusion of other variables.

A discrete choice approach, which investigates the effect of water source choice on water demand in countries where several choices of public water supply are usually presented to the consumers, was introduced in the water demand literature by Mu, *et al.*, (1990). They based their argument on the fact that models in developed countries can treat water as a homogenous goods, but this is not possible, for example, in an African village because water is a heterogeneous goods, with each source possibly providing water of different quality, reliability, and convenience in terms of accessibility. They analysed the functional relationship between the households' source choice decision as dependent variables, and the other explanatory variables, based on a survey of a sample of households in a village community in Kenya. The results suggest that the households' source decisions are influenced by the price of water and collection time.

More recently, in 1997, Clarke *et al.* proposed a new methodology for estimating household water demand using a modelling technique called microsimulation, which involves the estimation of micro-level data using chain conditional probabilities. Microsimulation has been successfully applied to the entire city of Leeds to estimate water demand by wards and enumeration districts. It was shown (Clarke, *et al.*, 1997) that this method is data-efficient, capable of predicting demand for 200,000 households by a small area, from a sample of 4,000 households, and has the potential to reflect population dynamics and attributes.

A large number of analytical studies in demand forecasting have appeared in the literature since the classic work of Howe and Linaweaver of 1967 has been published (Martin and Thomas, 1986). The vast majority of the literature cited has focused on the modelling and forecasting of residential and municipal water demands, whilst a relatively limited amount of literature has dealt with the agricultural and industrial water demands. The literature cited has shown that the demand for water is a function of a number of demographic, socio-economic, physical, technological, climatic, geographical, cultural, and attitudinal variables. The following paragraphs discuss some of the factors which appear in the literature to have influence on water use in the various water use activities, along with the main modelling approaches adopted and key methodological issues raised. Because each activity of water use responsds to a particular set of variables, it would seem wise to review the literature based on the influence of each of those variables separately.

Household Size

Water consumption is expected to increase as the number of persons per household increases up to a certain point, beyond which per capita consumption decreases as the household size increases. This is because there are economies of scale of water use with respect to household size (Grima, 1971; Morgan, 1973; Darr *et al.*, 1975; 1976; Tillman and Bryant, 1988). The reason for the expected negative sign of the beta coefficient in the case of this variable is that some uses of water (i.e. car washing, garden watering, clothes washing, etc.) take place regardless of the household size (Darr *et al.*, 1975; Bannaga; 1979; Bhattacharya; 1982). Grima (1972) further elaborated that as the number of persons in dwelling unit increases water uses are averaged over a larger number of persons.

The number of occupants has been found to be a valid predictor in a number of domestic water demand studies. For example, Howe and Linaweaver (1967) empirically showed that the number of persons per household determines an approximate total domestic usage, reflecting any economies of scale that may be possible in water use. Morgan (1973) used models of linear and log-linear forms to estimate the domestic water demand in Santa Barbara, California, based on analysis of a cross sectional data, supported by an opinion survey of a sample resident. In all the models developed, the obtained coefficients suggest that the number of people per dwelling unit is a significant determinant of water demand per dwelling unit, with per capita water use decreasing as family size increases.

For a sample of 1,892 metered and unmetered residents in four urban areas in Israel, Darr *et al.* (1975), stated that the number of persons per household is a valid predictor of water consumption in three urban areas, with elasticity ranging from -0.28 to -0.53. The total number of persons per family is strongly associated with the average monthly consumption per family in Panang Island, Malaysia, explaining almost 40% of the variance in household water consumption (Katzman, 1977). A study by Feachem *et al.* (1978), quoted in Bhattacharya (1982), provided further evidence of a decrease in per capita consumption with an increase in household size. According to Bannaga, (1979), household size also appeared to be one of the important parameters affecting water consumption in the town of Elobeid, Sudan; a unit increase in household size would reduce the per capita consumption by 0.277%. The result was statistically significant at the 1% level.

On the contrary, household size was found to be insignificant in explaining residential water demand in two other water use studies: in Metro Manila (Palencia, 1988) and in Central Pennsylvania (Seaker and Sharpe, 1988). Multiple regression techniques have been used to analyse past water use data by customer class in San Francisco (Metzner, 1989). The derived function indicates that the number of persons per household is strongly associated with average water consumption. Rather surprisingly, the number of persons per household is positive and is significant only in the western region of the United States; the other regions' coefficients are also positive, although not significant (Nieswiadomy (1992). In a cross-sectional survey of 473 family homes in Rammallah City (West Bank), Mimi (1999) concluded that number of occupants per household is statistically significant at the 0.05 level, with a slope coefficient of -8.374, though his reported model includes a number of insignificant variables and possibly suffers from multicollinearity problems as indicated by its high R^2 value. Household size, according to Gunatilake *et al.* (2001), also explains a significant portion of the water consumption in Kandy, Sri Lanka; the obtained slope coefficient was significant at the five percent probability level.

Household/Per capita Income

Many studies demonstrate a positive relationship between water use and income per household or per capita (Larson and Hudson, 1951; Billings and Jones, 1996; Berry and Bonem, 1974; Bryant and Tillam, 1988). Headley (1963) states that the income variable represents not only an ability to buy but also stands as proxy for such influences as water-using appliances, such as number of dishwashers and washing machines, the number of bathrooms, and the area of lawns and gardens. Obviously, water consumers tend to own more water-using appliances, swimming pools, and private gardens with the increase in their income. Also, water consumers tend to be less concerned about their water bills as their income goes up. The responsiveness of the quantity of water consumed to income level is measured by the income elasticity of demand, which is the percentage change in the quantity of water demanded, associated with the percentage change in household or per capita income, holding other factors such as price constant.

Headley (1963) used the median family income per year as an independent variable to study the relation of family income to the use of water for residential and commercial purposes from time-series data in the San Francisco Metropolitan area. His linear model yielded income elasticities of demand ranging from 0.0 to 0.40. Using a linear equation from cross-sectional data analysis of domestic consumption in metered public sewer areas in the United States, and the property value variable in thousands of dollars as a surrogate for income, Howe and Linaweaver (1967) measured an income elasticity of approximately 0.35. Average household income was shown to be a significant predictor of the per capita municipal water demand in Chicago, with a correlation coefficient of 0.195, significant at the 0.02 level according to Wong (1972). A bivariate regression model relating the average daily municipal water use to the per capita income was developed by Berry and Bonem (1974), and yielded the regression equation of the form: $q = 25.1 + 0.059y$, with $R^2 = 0.766$, where q is the daily municipal water use in gcpd, and y is the per capita income in dollars. Darr *et al.* (1975) also noted that income per capita is one of the principal factors influencing water consumption in Israel.

A cross-sectional analysis of a random sample of 1,400 households in Panang Island, Malaysia, indicates an income elasticity of demand of zero for low-income families and an elasticity of 0.2 to 0.4 for higher income families (Katzman, 1977). Hanke and de Mare (1982) argued that a pooled time-series cross-sectional analysis yields more efficient estimators for regression equations than either pure time-series or pure cross-sectional analysis because, among other reasons, pooling allows researchers to include variables that vary over time or over household but do not vary over both dimensions. The analysis of their pooled data for the city of Malmo, Sweden, derived a linear model that showed a statistically significant income elasticity of 0.11.

Cochran and Cotton (1985) used simple linear and logarithmic equations from a longitudinal survey in Oklahoma City and Tulsa, which indicated that average price and per capita income were predictive variables for Oklahoma City's water demand, while only per capita income was found to be a valid predictor for consumption in Tulsa. Per capita income was found to be statistically significant at the 0.01 level, with beta coefficients of 6.1852 and 0.5793, and R^2 of 0.94 and 0.93, for the linear and log-linear models, respectively. However, these high R^2 values for cross-sectional data may indicate presence of multicollinearity. In a study by Bryant and Tillman (1988) using time-series data from the City of Hays, Kansas, family income was shown to be the best predictor for water demand in the area, explaining 39% of the variation in water consumption. Empirical evidence from the study suggests income elasticity of demand in the range from 0.264 to 1.744.

A derived linear regression equation for time-series data from Metro Manila (Palencia, 1988) was in the form: $RU = 20.129 + 0.0253Y - 18.926 - 1.776DP$. The Y variable (average income per month per household) was significant at one percent significance level. The estimated elasticity of demand with respect to this variable was 0.541. In the work of Gunatilake *et al.* (2001), a set of demand functions were tested, of which the log-log model was found to provide better statistical results. Income elasticity had a positive sign, but was inelastic (0.08), indicating that income increase will only have a marginal impact on water consumption. Using monthly aggregate data from 1994 to 1998, Hussain *et al.* (2002) developed residential water demand models of both linear and log-log forms. In the linear model, the income (per capita GNP was used as a proxy for income) coefficient was 1,765.28 and was statistically significant at the 1% level. The resulting income coefficient from the log-log specification was 0.47, again statistically significant at the 0.001 level. The estimated income elasticities of demand were 0.43 and 0.47 for the linear and log-log specifications, respectively.

Price of Water

On the basis of consumer demand theory, one would expect that water consumption at both aggregated and disaggregated levels is sensitive to price change. Empirical evidence from numerous water demand literature suggests that, particularly in metered consumptions, demand for water is price-inelastic, and is negatively correlated with quantity demanded (the higher the price of water, the lower the water use will be). The term elasticity refers to the responsiveness of the quantity of water demanded to a change in price (i.e. represents the percentage change in the quantity of water consumed divided by the percentage change in its price).

The literature dealing with the price/water demand relationship has grown steadily in size and sophistication throughout the past several decades (Carver and Boland, 1980). Numerous water demand studies have investigated the impact and elasticity of price on water demand (Gottlieb, 1963; Howe and Linaweaver, 1967; Wong, 1972; Young, 1973; Turvey, 1976; Gibbs, 1978; Foster and Beattie, 1979; 1981; Griffin *et al.*, 1981; Hanke and de Mare, 1982; Billings, 1982).

A great deal of controversy in this literature revolves around the choice of the appropriate price specification to include in regression equations. While some researchers (e.g. Gottlieb, 1963; Wong, 1972; Young, 1973; Foster and Beattie, 1979; 1981) utilised average price variable models, which yielded price elasticity of demand ranging from - 0.33 to - 0.656; others, including Howe and Linaweaver, 1967; Turvey, 1976; Gibbs, 1978; Billings and Agthe, 1980; Griffin *et al.*, 1981; Billings, 1982; Howe, 1982 have developed marginal price variable models that also showed significant price elasticities.

More recent work shows that there has been a reluctance to use the average price approach, especially when block rate pricing strategy is being implemented. For example, (Gibbs, 1978; Griffin *et al.*, 1981) claimed that the average price is unsuitable for use in investigating the effect of price on water consumption, on the ground that average price models significantly overestimate the response of consumption to price change. They consequently concluded that the appropriate measure of customer responsiveness to increase in price is the marginal price. Foster and Beattie (1979; 1981) opposed this view by arguing that the results of the water demand studies support their view that price specification conforming to marginal analysis is not necessary. This school of thought, as explained by Young (1996), contends that because water represents a small portion of expenditure, consumers do not find it in their interest to become informed on the details of the rate schedule; so marginal price is less relevant than average price.

Billings and Agthe (1980), added another dimension to this debate by claiming that both average price and marginal price alone were not sufficient to determine the demand function in the case of block rate pricing structures. In their own words "…. while using average price alone tends to produce large estimates of price elasticity in the block rate system, using marginal price alone would result in income effects not properly accounted for". They, alternatively, suggested two price-related variables: the marginal price variable and the difference price variable (which represents the difference between the actual payment for water and what the payment would be at the marginal price). Foster and Beattie (1981) rejected this argument by stating that the empirical work of Billings and Agthe gave scant evidence that marginal price and difference price variables were the proper specification in demand studies of an aggregate nature. They used an ordinary least squares to estimate multiple regression coefficients using both maginal price and average price specifications. Their results indicated that the average price model would appear to be superior in terms of the amount of variance explained, parameters estimates and their significance, and F statistics.

The works by Gibbs (1978) and Nieswiadomy (1992) provided excellent and interesting discussions on the difference in estimation between the average price and marginal price models. While the former observed that average price models tend significantly to overestimate the consumers response to change in price, the latter strongly indicates, using Shin's (1985) price perception model (a model that tests whether consumers react to average or marginal price) that consumers react more to average price than to marginal price. Ziegler and Bell (1984), tested the null hypothesis that there is no significant difference in the estimates of industrial water demand using either average or marginal prices. Their findings suggested that the use of average price provides a better estimate of water use in terms of statistical fit and predictive capabilities.

Martin and Thomas (1986), questioned whether this emphasis on econometric precision is necessary where policy-making rather than methods development or testing of theory is concerned. They argued that irrespective of what model is the true model, important policy conclusions might be made without econometric study or precise knowledge of point price elasticities. At this point, it seems that the choice of a specific price variable to estimate and forecast the demand for water, or perhaps even ignorance of price effect if a given system or situation imposes such an approach, will remain an open issue.

Nevertheless, as already mentioned, water demand models with price variable included in the specification are abundant in the literature. From cross-sectional data of 39 master-metered residential areas in the United States, Howe and Linaweaver (1967) formulate models of residential water demand that differentiate not only between domestic (in-house) and sprinkling uses but also among metered, flat-rate, septic tank, and apartment areas. Domestic demand, which was estimated using a linear equation, was found to be relatively inelastic with respect to price, with price elasticity of -0.231. Sprinkling demand was estimated using a log-linear functional form. The results showed a price elasticity of -1.12 for all metered areas, and price elasticities of -0.70 for the western region and -1.57 for the eastern region. The maximum day sprinkling demands were found to be inelastic in the west but relatively elastic in the east.

Wong (1972) used an ordinary least squares regression model to study the municipal water demand in Chicago, Illinois, using pooled time series and cross sectional data, with the average price being an explanatory variable. For the time-series data, while price was found to be an insignificant predictor (elasticity -0.02) in Chicago, it was significant at the 5% level for Chicago's outside communities (elasticity -0.28). The price elasticity of demand for the cross-sectional data was found to be higher than that of the time series analysis, ranging from -0.26 to -0.82 for Chicago and outside communities, respectively. Young (1973) demonstrated a shift in the price elasticity of demand using two sets of time series data of Tucson, Arizona. Price elasticities of -0.63 and -0.41 were reported for the 1946 – 1964, and 1965 – 1971 data sets, respectively.

Bannaga (1979) noticed that water pricing in Elobeid, Sudan, varies between areas inside the town; this variation is linked to the accessibility to water. The partial correlation coefficient (-0.195, significant at 0.003 level) in his model indicates that a negative relationship exists between water consumption and cost of water. Gibbs (1978) illustrated the difference of price elasticities for two models: one utilised average price, the other marginal price. Elasticities estimated were -0.62 and -0.51 for the average price and marginal price models, respectively; both coefficients were statistically different from zero at the 0.01 level.

A dynamic model that explicitly took into account the dynamic relationship between the current and past data in a form of year-to-year linkage was developed by Agthe and Billings (1980). This model, which was used to estimate the residential water demand in Tucson-Arizona, allowed estimation of both long and short-run price elasticities of demand using both linear and log-linear form equations. Hanke and de Mare, in 1982, applied an ordinary least squares model to estimate the impact of price changes on the demand for residential water in Malmo, Sweden, using pooled time series, cross-sectional data. Their model showed an average marginal price elasticity of demand of -0.15, and yielded a very low R^2 (0.259), which was considered satisfactory for such a pooled analysis.

Thomas and Syme (1988) employed a survey-oriented approach, in which consumers are asked to state their willingness to pay, or reaction to a possible increase in water price. Although this method had been widely used to estimate the values of non-measurable variables, Thomas and Syme found it very useful in identifying the demand-price relationship of different components of household use. On the basis of cross-sectional data from Rammallah District (West Bank), Mimi (1999), reported that price correlates inversely to water use (elasticity -0.374, significant at 0.001 level). Time-series monthly data for a six-year period (1994 – 1999) for randomly selected 40 households were analysed by Gunatilake *et al.* (2001) to estimate the demand for domestic water in Sri Lanka. Price elasticity (marginal) was estimated to be -0.34, significant at 0.05 level.

Agthe and Billings (2002) examined the effect of price on water use per apartment. Their model was developed using ordinary least squares regression for winter and summer water demands in Tucson, Arizona. Water price was found to be significantly and negatively related to apartment complex water use for both seasons. Price elasticities of -0.73 and -0.45 were estimated for the summer and winter demands, respectively.

Investigations by Thompson and Young (1973); De Rooy (1974); Ziegler and Bell (1984); Renzetti, (1988); Hussain *et al.* (2002) and others, demonstrated that price had also a significant effect on industrial water demand. De Rooy, in 1974, explained the sensitivity of the industrial demand to changes in price. The application of his approach (mix-regression) yielded some important evidence that industrial firms generally respond to an increase in water price by reducing their water use. In a study conducted by Stone and Whittington (1984) for the Dutch paper industry, the authors found effluent charge (a proxy for price of water) statistically different from zero at more than 93% confidence level and had the expected negative sign. William and Suh (1986) addressed the price/water demand relationship in the commercial and industrial sectors. Their ordinary least squares model of log-linear type showed that demand in the commercial class was relatively price inelastic, irrespective of which price measure was selected, and that the industrial water consumption was relatively more sensitive to price variation.

A double-log model (Renzetti, 1988) was used to model the industrial water demand in British Colombia, Canada, for four aspects of demands; intake, treatment prior to use, re-circulation, and treatment prior to discharge for four manufacturing sub-groups. The resulting figures showed water intake price elasticities range from -0.12 to -0.54. Separate water-demand functions for residential, commercial, and industrial sectors were estimated using monthly time-series data (Hussain *et al.*, 2002). In general, the price was found to have a significant effect on water demand, and this effect was much higher for the industrial sector than for the residential and commercial sectors. Estimated price elasticities were -0.18, -0.17, and -1.34 for the residential, commercial, and industrial water demand, respectively.

Property Value

Property value in the water demand literature is normally used as a surrogate variable for income. Generally, a positive relationship is observed between water consumption and household rateable value. In a comparison of per capita residential water use in five towns in Detroit Metropolitan Area, USA, Bogue (1963) cited in Bhattacharya (1982), showed that the average daily per capita water use increased from 75 gallons to 136 gallons as average home value increased from $11,000 to $28,000. In the model developed by Howe and Linaweaver (1967) for domestic demand, market value of the dwelling unit was found to be a significant predictor of water demand, with a correlation coefficient of 0.76. Linear and log-linear equations were fitted to a sample of metered single unit-dwellings (Grima, 1973). Assessed sales value of residence in hundred of dollars was among a number of variables hypothesised to have an impact on total water use, and was found to be statistically significant at the 0.01 level.

Thackray *et al.* (1978) observed that the average consumption within groups of similar rateable values follows a reasonable linear trend, but the overall dispersion is very great and the individual relationship between rateable value and consumption is found to be very small. Average rateable value as an indication of group average consumption explains 63% of the variation in water consumption, but rateable value as indication of individual household consumption explains only 3% of the variation. Using pooled time series cross-sectional observations for 261 residential households in Raleigh, North Carolina, demand relations were estimated for total residential, winter, and sprinkling demands (Danielson, 1979). The coefficient of house value was estimated to be 0.363 and was nearly identical to income elasticity for winter and total residential demands.

In a study of outside and total water uses of eight homes in Central Pennsylvania, it was noted (Seaker and Sharpe, 1988) that there was a strong positive correlation between assessed home value as a measure of income level and total per capita water use, with more water being used in more expensive homes. Such a relation, however, appeared to be insignificant in the case of outside water use. The analysis of winter data in metered and sewered single-family homes from Anaheim, Southern California, using the IWR-MAIN model, generated a statistically significant partial coefficient for the market value of the housing unit (Dziegielewski and Boland, 1989). A unit ($1,000) increase in this variable would produce a 0.994 increase in the quantity of water consumed (expressed in gallons per day).

Type of Dwelling

Obviously, water consumption will vary depending on the type of dwelling, since the latter normally reflects wide variations in factors such as plot size, number of rooms, number of bathrooms, garden area, and diversity of household fixtures, etc. Age of household may also be considered to be one of these physical factors. According to Howe and Linaweaver (1967), a positive relationship appeared to exist between type of dwelling and average annual quantity demanded for domestic purposes. Jenking (1973), found that analysis of water consumption in Fylde, England, showed that 35% more water is consumed in private dwellings than in council properties. This was explained by the additional water fittings in private properties. Thirty two percent of council dwellings did not have any additional fittings compared to 13% in the private sector. In Malvern, United Kingdom, privately owned dwellings consumption was 52% more than in council dwellings, and that consumption per property per day showed a regular incremental pattern with increase in plot size represented by the number of bedrooms (Jenking, 1973).

The type of dwelling on the contrary was not found to be a valid predictor in the case of Eilat, Israel (Darr *et al.* 1976). Thackray *et al.* (1978), presented a useful comparison of the per capita daily consumptions in different type of dwellings in Malvern and Mansfield, United Kingdom. Detached houses appeared to have more per capita daily consumption than other type of houses in both Malvern and Mansfield. This was also the conclusion reached by Russac *et al.* (1991) who discovered that detached houses had by far the highest consumption, with bungalows using about half of that used by detached houses, and flats and mixed accommodation using about 40% of the consumption of the detached houses.

In their sprinkling demand model, Howe and Linaweaver (1967), reported that irrigable area per dwelling unit was highly positively related to water consumption. Gardner and Schick (1964) cited in Bhattacharya (1982), demonstrated that, in Northern Utah, per capita garden area was a highly significant variable influencing the daily per capita consumption. One percent increase in the per capita lot area was associated with a 0.15 percent increase in the per capita consumption. The responsiveness of the single-family residential lot size as independent variable to the water use was estimated by Willsie and Pratt (1974). Use of water by single-family residents was found to be highly responsive to changes in lot size.

In a double-log model developed by Clouser and Miller (1980) for two communities in the United States, the number of bathrooms was found to be a weak predictor for per capita water consumption. (Mimi, 1999), however, observed that the number of rooms, garden area, and household area did not have a statistically significant effect on domestic water consumption in the West Bank. In the case of number of rooms per dwelling, the same conclusion was reached by Darr *et al.* (1976), who recognised that this variable was highly correlated with the number of persons per dwelling unit; and found that it was significant when included with the income variable alone. Taher and Al-Saati (1999) developed residential demand models on a cross-sectional survey of 195 randomly selected households from the city of Riyadh, Saudi Arabia. The generated models indicated that, although the obtained R^2 values were notably low, both the household type and plot size were significant predictors. Consumers living in villas use more water than those living in apartment buildings. In two of the three groups studied, plot size was the major factor in explaining variation in water use.

Bhattacharya (1982) found that the influence of age of property on household water use is a mixed one; for example, while old properties tend to have fewer fixtures which have a negative effect, ageing increases leakage in the plumping system and, therefore, raises invisible consumption. Howe and Linaweaver (1967) reported a very weak negative relationship between the age of dwelling and the in-house domestic water use. The relationship between the average per capita water consumption and the age of property was well demonstrated by Thackray *et al.* (1978) in their Malvern and Mansfield study. Their findings indicate that newer properties tend to use more water in terms of per capita consumption; this was primarily explained by the increase ownership of water-using appliances in the new dwellings. Hanke and de Mare (1982) also showed that the age of the household was an important determinant of the quantity of water used per house.

Weather Variables

Factors reflecting climatic conditions appeared in the literature to have a major impact on water use. This is particularly true in arid and semi-arid areas. Changes in these variables are very significant when observed on a monthly or seasonal basis, such as between summer and winter (Palencia, 1988). Wong (1972) noted that the average summer temperature was an important correlate to residential water use in Chicago and its outside communities. For the outside communities, outside average summer temperature had the most significant effect; significant at the 0.02 level. By revising the WRD 1966 forecast for South-East England, Rees and Rees (1972) proved that inclusion of a weather variable (mean summer rainfall in this case) significantly improved the forecasting capabilities of the previous water demand models. Young (1973) observed that both temperature and evaporation did not have significant effect on water use, while the rainfall effect was found to be statistically significant at the 10% probability level for the 1946 – 1964 data set. The measured effect of rainfall implies a 4,000 gallons per year decrease in consumption for each additional 1 inch of rain. For the 1965 – 1971 period, however, the coefficient of rain was not statistically significant.

Willsie and Pratt (1974) developed a regression equation that relates average daily water use to both average inches of precipitation per day, and average daily temperature. The variables explained about 91% of the variation in daily water use. Surprisingly enough, climatological variables (rainfall and temperature) were found to be invalid predictors for the per capita water use in a number of New Mexico towns, but this finding was attributed to insufficiency of precise data (Berry and Bonem, 1974). The work by Morgan and Smolen (1976) focused on the use of various climatic indicators in estimating municipal water demand. Three alternative climatic indicators were tested: potential evaporation minus precipitation, temperature and precipitation, and monthly binary seasonal variables. It was shown that temperature and rainfall provided the best climatic variables for a model specification.

In his sprinkling demand function, Danielson (1979) noticed that the climatic variables played a major role in estimating sprinkling demand. The obtained rainfall elasticity of -0.206 indicates that an inch decrease in rainfall would increase water demand for sprinkling by 5%. A 10% increase in average temperature was associated with an increase in consumption of 51%, or over 14 gallons per house per day. Hansen and Narayanan (1981) applied a time series regression model for data from the Salt Lake City Water Department; the average temperature, total precipitation, and percentage of daylight hours were tested in the model as independent variables. All the weather variables tested were significant, and all had the expected signs. Claborn *et al.* (1988) found that water usage is highly correlated with maximum daily temperature and precipitation. Periods of significantly higher water use began when the maximum daily temperature reached about 70 degrees F for a sustained period, and decreased suddenly in response to rainfall. Using both maximum temperature and precipitation as independent variables, a significant correlation coefficient of 0.725 was obtained.

Miaou (1990) examined monthly time series data from Austin, Texas, and noted that the number of rainy days per month is a consistently better explanatory variable, and that the proposed non-linear models outperform the linear models in describing water use variations under different climatic conditions. Nieswiadomy (1992) also found that rainfall and temperature variables were significantly different from zero in all regions of the United States except the Northeast. The study by Hussain *et al.* (2002) estimated demand functions for residential, commercial, and industrial uses, using cross-sectional data from Sri Lanka. The average monthly rainfall and average monthly temperature were among the independent variables included in their models. For the residential demand models, average monthly temperature was significant at the one percent level, whilst rainfall, although it had an expected negative sign, was not significant. In the case of the commercial sector, rainfall was also statistically insignificant plus having a positive sign, which was contrary to the expectation. In both the commercial and industrial sectors, the average monthly temperature was statistically significant and had the expected sign.

Ownership of Water-using Appliances and Technological Changes

Ownership of water-using appliances, including the presence of a swimming pool and waste-disposal unit, connection to the sewer, and other household technological changes has been reported in a number of water demand studies to have significant effects on water use (e.g. Batchelor, 1975; Thackray et. al., 1978; Powers *et al.*, 1981; Thomas and Syme, 1988). The contention is that as usage or ownership of water-using appliances increases, household water use should increase. For example, based on a random sample of 1,388 households in Malvern, United Kingdom, (Batchelor, 1975), found that the effects of the variation in household technology and appliances, except for bathroom showers, on household water use were significantly positive. His findings confirmed the importance of durable goods ownership in shifting domestic water demand. Thackray *et al.* (1978) observed that the ownership of an automatic washing machine was associated with a higher average consumption; the same cannot be said in the case of the ownership of any other type of washing machine, which did not appear to be related to a higher average consumption.

In a survey of 100 sample residents in Townsville, USA, it was disclosed, (Powers *et al.*, 1981), that the percentage of toilet flushing, bathing and showering, and clothes washing were the major components of in-house consumption accounting for approximately 82% of the total consumption. The in-house model was used to simulate the effect of changing appliances ownership patterns. The resultant figures indicated that the average consumption was relatively insensitive to anything other than really dramatic changes in ownership level of some appliances (Powers *et al.*, 1981). This is in line with the conclusion reached by Thackray *et al.* (1978).

A study to determine the effect of water intensive appliances or activities on household water consumption in two communities during different periods was undertaken by Clouser and Miller (1980). Activities included in the study were the use of washing machines and dishwashers, and lawn watering. In the majority of cases, these activities, particularly the use of dishwashers and washing machines, increased water consumption and were statistically significant explanatory variables. The swimming pool variable was significant at the five percent level in community A, and the one percent level in community B. Key water-using fixtures and appliances, outside hose bibs and total household water use were monitored by Seaker and Sharpe (1988) for a 28 day period in eight homes in Central Pennsylvania. Mean daily per capita water use for toilet flushing, showering and bathing, and clothes washing were found to be higher than literature values. Demand for in-house and outside uses appeared to be strongly dependent of water using activities; while water use did not appear to be affected significantly by use of an on-lot sewage disposal system. Presence of a swimming pool was found to be an important determinant of outdoor water use.

The effect of lawn watering and sprinkling demand on total and outside water uses has been widely investigated by various workers (e.g. Howe and Linaweaver, 1967; Danielson, 1979; Clouser and Miller, 1980; Powers *et al.*, 1981; Seaker and Sharpe, 1988). In most of the studies cited, these variables were significant and were indicative of more consumption. Car washing was also found to be an important demand-determinant variable in a number of water demand studies (see, for example, Batchelor 1975; Thackray *et al.*, 1978; Akintola and Areola, 1980). For data from Perth Metropolitan Area, Australia, Thomas and Syme (1988), used a general linear model to forecast the residential water demand, in which they used the percentage of households with a private groundwater bore as an independent variable to examine the effect of technology; the analysis indicated a satisfactory statistical result. It was found (Joseph, 1982) that non-sewered consumers appear to consume less water than sewered consumers.

Household Composition

This variable is normally expressed in terms of the percentage number of children and elderly people per household. Bannaga (1979) argued that it seems reasonable to assume that a large number of children reduces the level of per capita consumption, because children require less water than adults. With some exceptions, adults tend to use more water than teenagers, and old people aged over 65 generally make less use of water for personal purposes as compared to other adults (Bhattacharya, 1982). Therefore, the relationship between household water use and household composition (represented by the percentage of children per household) was expected to have a negative sign. Bennett and Linstedt (1975) reported in Bhattacharya (1982) observed that the average daily use of water by adults was 19.5% higher than by teenagers, and teenagers used 20.6% more water than children. The analysis of cross-sectional data from Elobeid, Sudan, produced a partial correlation coefficient of -0.163 (significant at the 0.01 level) between the number of children and the per capita consumption (Bannaga, 1979).

Hanke and de Mare, in 1982, also reported a highly significant result of this variable from their pooled time-series cross-sectional analysis in Malmo, Sweden. Murdock *et al.* (1991) found that households with a younger householder use more water than households with an older householder (402.0 versus 354.5 gallons) and, according to Mimi (1999), the number of children per household was shown to be an important determinant (significant at the 0.05% level) of the average daily per capita consumption. For the various user groups surveyed in the city of Riyadh, Saudi Arabia, the number of children per household was found to be a significant predictor for water use (Taher and Al-Saati, 1999). Their findings indicated an expected inverse relationship.

Mu *et al.* (1990) compared the results of the traditional ordinary least squares models with the results of their proposed discrete choice model referred to earlier in this section. For all functional forms of the traditional model, the number of adult women in the household as a proportion of household size had the expected sign and was significant at the 5% level of significance. In the discrete choice model, the explanatory variable number of women (defined here as the number of adult women in the household, rather than the proportion of women) was expected to have a negative effect on the probability of the household choosing a water vendor and a positive effect on the probability of the household choosing a well. The analysis suggests that the number of women in a house significantly affect a household's decision on which source of water to use. The effect of age distribution on water consumption was also investigated by Russac *et al.* (1991) who noted a considerable difference in consumption for the single-person household between the adults of working age and those who were retired. On average, the retired householder uses almost 70% more water than the adult of working age; but this difference is far less in the case of a household of two members.

Level of Education

The expectation is that there is a positive relationship between the level of education and water use. Darr *et al.* (1976) noted that per capita consumption and educational level vary with each other. They found that when family size and income level were held constant, in each group, except the small group, low-income families, families in which the respondent had at least eleven years of schooling consumed more per capita than families in which the respondent had ten or fewer years of schooling. The level of education seems to be closely related to water use; with basic education achieved, consumption per capita is likely to increase (Bannaga, 1979). For people relying on public standpipes, the level of education was more closely related to water use ($r = 0.623$, significant at the 0.001 level) than for those with house connection from the public supply ($r = 0.249$, significant at the 0.001 significance level). Bannaga's linear model yielded a partial coefficient for educational level of 0.146 (significant at the 0.02 level).

The sign of variable education expressed as the number of formal years of education of household members was found to be negative (different than hypothesised), and was not significant in any of the four traditional functional forms tested (Mu *et al.* (1990). For the discrete choice model people with higher education (defined as in the traditional model) were hypothesised to be more likely to avoid consuming poor quality water because of greater awareness of the health risks. Therefore, households with higher level of education were expected to choose a vendor. Although the signs of the education variable were as expected, the reported coefficients were insignificant.

Conservation and Policy Variables

Water conservation practices and policy instruments variables in terms of pricing policy, metering, by-laws on plumbing and fixtures, rationing and water use restrictions, and peak summer charges, etc. are normally hypothesised to have significant impacts on water consumption. Apparently, conservation practices and policy intervention measures encourage a substantial potential for water savings. Grima (1973) demonstrated that residential water demand management aims at the conservation of water use as a means of making a more efficient use of the available resources, and that, by influencing water demands, management can affect the level and timing of additional plants required to meet the demand. Therefore, according to Grima (1973), forecasting and designing of water supply systems should take into account policy variables and conservation measures such as metering, level of marginal commodity charges, and other non-price alternative such as smaller plumping fixtures, use of water saving devices, etc.

Hanke (1970) analysed the effects on residential demand of changing from a flat rate price structure to a metered one, using a time series data from Boulder, Colorado. The evidence generated from the analysis demonstrated that water users did not return to their old use patterns after meters were installed, and that water consumption in the study area grew less rapidly after metering was introduced. Rees (1971), reported in Batchelor (1975), found that the rate of growth of demand in Malvern, England, fell in periods after price increases were implemented. Berry (1972) reported that the actual reduction in consumption in Honiara, British Solomon Islands, following metering was 43%, taking into account the increase in the number of consumers. By allowing adjustments for the government consumers who do not pay directly for the water they use, the actual reduction in the commercial and domestic sectors during the first year of metering is virtually 50%.

In a model developed for the Corps of Engineers, USA (Sonnen and Evenson, 1979), it was shown that choosing a numerical conservation target to be achieved was more meaningful and yielded more predictable results than price or price elasticity manipulation. A 10% conservation assumption for all land uses, with respect to both indoor and outdoor uses of water, led to a greater reduction in demand than with a 50% increase in price. A 40% conservation assumption showed a marked reduction (40%) in total water demand predictions. Hanke and Mehrez (1979) developed statistical models to assess the effects of water restrictions on water consumption using time series data (1946 – 1975) from Perth, Western Australia. Water use restriction was introduced to the model as a dummy variable, which received the value of 2 if restrictions were used during a particular month, and 1 if restrictions were not used in a particular month. The resulting figures indicated that imposition of water use restrictions reduces estimates of water use by approximately 14%.

Clouser and Miller (1980) investigated the implications of conservation on water consumption by asking households about their knowledge of water saving devices. Their findings revealed that households included in the study were not familiar with water saving devices available in the retail market, and thus concluded that the potential to decrease water use by households adopting water saving appliances was extremely high. Martin and Thomas (1986) investigate the importance of short-run and long-run elasticities on policy purposes for urban residential water demand. They conclude that short-run elasticities give little information for policy purposes, but in the case of long-run pricing policy decisions, the potential for price adjustments to affect use is enormous.

A statistical model to estimate the effects of short-term conservation measures on daily water demand is applied in two case studies in southeastern United States (Little and Moreau, 1991). In Case Study 1, Camden, South Carolina, the effect of conservation was shown to reduce the daily water demand by 14.9%, whilst in Case Study 2, conservation measures were shown to have negligible effects on the daily water demand; a conservation saving of only 0.1% was estimated. In a survey of 430 (of the 600 largest) U.S. utilities undertaken by Nieswiadomy (1992), the conclusion was that conservation did not appear to reduce water use, but public education appeared to have reduced water usage in the western region. Water use restrictions as a means for conservation were, however, found to be a statistically significant predictor for water use in Perth, Western Australia, for all the estimated five functional forms (Thomas and Syme, 1988).

From a detailed study of industrial and commercial water use undertaken by the Severn-Trent Water Authority, Thackray and Archibald (1981), reported that, in total, recycling reduces water demand by 67%. Dziegielewski (1988) also presented figures to suggest that substantial water savings could be achieved by investing in sophisticated re-cycling techniques in manufacturing plants. Conservation opportunities in commercial and institutional establishments might also involve re-circulation of water used for cooling in air conditioning systems.

Number of Employees

Some studies, which investigated the influence of the number of persons employed in industrial and commercial establishments, suggest that the number of employees closely correlates with water use. For example, Klimek (1972) derived a demand function that relates the daily withdrawal by industry to the intake per employee, and other variables associated with employment and output per employee. A log-linear model of a basic form: $\ln Q = 4.42 + 0.81 \ln E$, where Q is the predicted average annual establishment water use in gallons per day, and E is the number of employees, was estimated by Dziegielewski (1988) using a national sample of 3,397 establishments in the United States. The independent variable (number of employees) was found to explain 34% of the variation in water demand. The regression coefficient of 0.81 reflects economies of scale within the establishments sampled with respect to water use per employee.

Malla and Gopalakrishnan (1999) conducted an empirical study to estimate the effect of several explanatory variables on the quantity of water consumed in the food processing and non-food processing industries in Hawaii, using ordinary least squares (OLS) and general least squares (GLS) procedures. The number of employee was used as surrogate for output level, and was found to be significant at the 5% level of probability in the food processing industry. The coefficients of this variable were positive in the case of total water, but negative in the case of water per employee equations. The coefficients of number of employees had positive signs and were significant at the 5% level in only the OLS equations in the non-food processing industry.

Level of Output

There is a positive correlation between industrial water demand and the level of production, but economies of scale may operate at certain levels of output. According to De Rooy (1974), demand for industrial water was found to be significantly affected by changes in output in a group of chemical plants in the United States. Thackray and Archibald (1981) estimated the elasticity coefficient relating water demand changes to output changes at about 0.5, implying that a 5% fall in output would reduce water demand by about 2.5%. Investigation into the character of water use in British Columbia, Canada, suggested that industrial water demand is characterised by a significant degree of sensitivity, in addition to the price of water, to the level of output produced by the firm (Renzetti, 1988). Most of the estimated coefficients of this variable for the four types of industries studied were significant at the 0.05% level, with the correct expected signs. However, the same was not true for the study of the Dutch paper industry referred to earlier (Stone and Whittington, 1984), where output did not have a significant coefficient and was eliminated from further analysis.

Type of Production

The industrial water requirement is the direct result of the volume and type of industrial activities (Joseph, 1982). Numerous water demand studies, including Thackray and Archibald, 1981; Joseph, 1982; Stone and Whittington, 1984; Malla and Gopalakrishnan, 1999 have demonstrated the role of type of production on industrial water demand. Using data from a sample of paper and chemical self-supplied firms in Arkansas, U. S., the dummy variable representing the industrial type was found to be significant and, as expected, inversely related to the use of intake water (Ziegler and Bell, 1984).

Technological Improvements

Several water demand studies have concluded that demand for industrial water is significantly affected by technological advancement. For example, from a survey of water use by a group of large chemical manufacturing plants in northern New Jersey, U.S., De Rooy (1974) estimated a demand function, which showed a highly significant coefficient of the technological variable. Stevens and Kalter (1975) found that technological factors were one of the major factors affecting the demand for water per unit of petroleum refined. Intake water demands decrease with increase in the level of process technology. Ziegler and Bell (1984) found that the technology variable was significant in determining the quantity of intake water used by a firm. The negative sign in their models indicated that the quantity of intake water varied inversely with technological improvements. A dummy variable representing the type of technology was found to be an insignificant predictor of water intake per unit of product output in an ordinary least squares regression developed to estimate a linear industrial water demand function for the paper industry in the Netherlands (Stone and Whittington, 1984).

Economic Growth

Economic growth encourages industrial development and raises the standard of living; hence, increase water use in both municipal and industrial sectors. The effects of a rising standard of living on municipal and residential water uses have already been implicitly highlighted earlier. In the case of industrial demand, Lahr (1982), for example, recognised a close link between water demand in the Dutch industry and the economic growth. His rough estimates indicated that a 2% growth in the economy would mean a growth of about 3.8% in industrial water demand, because the branches of industry, which required large amounts of water were expanding faster than branches with low specific water requirements. Mitchell *et al.* (2000) also showed that both commercial and industrial demands in the United Kingdom were highly sensitive to changes in the economy.

In the case of agricultural water demand, a number of numerical examples, including linear and non-linear programming techniques, have been reported in the literature for investigation of many variables that are recognised to have influence on the irrigation water demands (Kindler, 1988). These include, among others, crop patterns; crop yield; soil moisture and type; climatic factors; size of cultivated area; irrigation systems; price of irrigation; and factor inputs of agricultural production such as seed, fertilizers, machinery, labour, etc. For example, in 1967, a linear programming model was developed to forecast the agriculture water demand in the United States (Heady, 1967, quoted in United Nations, 1976). The model was formulated as a linear programmme whose solution gave the least costly distribution of agricultural production by crop type and region, under different assumptions about resource availability and costs, farm support programmes and consumer demand for agricultural products.

Gisser (1970) applied parametric linear programming methods to estimate the agricultural demand function for imported water in the Pecos basin, New Mexico. The main inputs to the model were land area, total profit, prices of local and imported water, and irrigation techniques used. Various agricultural demand functions were obtained for the basin. These functions illustrated the expected quantities of imported water that would be demanded at different prices and under a variety of constraints. Based on the model results, the author concluded that the model was able to set price ranges to which farmers would react to use either local water or imported irrigation.

In a study conducted by Maidment and Hutchinson (1984), a simulation model was developed to assess the water demands for large irrigation areas in New Zealand. Per unit area irrigation demands were first estimated for each identified unique combination of soil, crop type and irrigation strategy using daily soil moisture balance simulation over a number of seasons of recorded climatic data. These were then combined using crop areas and efficiency weights to give time patterns of areally aggregated irrigation water demand. Using a multiperiod mathematical linear programming model to estimate demand for supplemental irrigation in the Lower Mississippi Valley, projections of demand for supplementary irrigation were made for three parishes in northern Louisiana at 5-year intervals, with 1985 as the base year, up to the year 2000 (Henning, 1989). The objective function of the model was to maximise the net return for each parish. The inputs to the model were crop water requirements, yield potentials of the different soil units, and irrigation costs. The results indicated significant economic potential for expanding supplemental irrigation in the region, and the model could be used to evaluate alternative scenarios for agricultural water use due to changes in the allocation process, conservation of soil and/or water, and water quality.

Bailey and Minhinick (1989) conducted a quantitive analysis of irrigation requirements in different climatic areas of England and Wales. The analysis takes accounts of the differing requirements of various crops and variation in soil texture. The results include an estimation of irrigation requirements in an average year, a typical dry year, and an exceptional year such as 1976. It was found that the developed model was capable of obtaining an approximate irrigation requirement for a range of crops, grown in a range of soils, in each of the designated climatic areas 2-7, except Area 1, for which the model indicated that no irrigation was required.

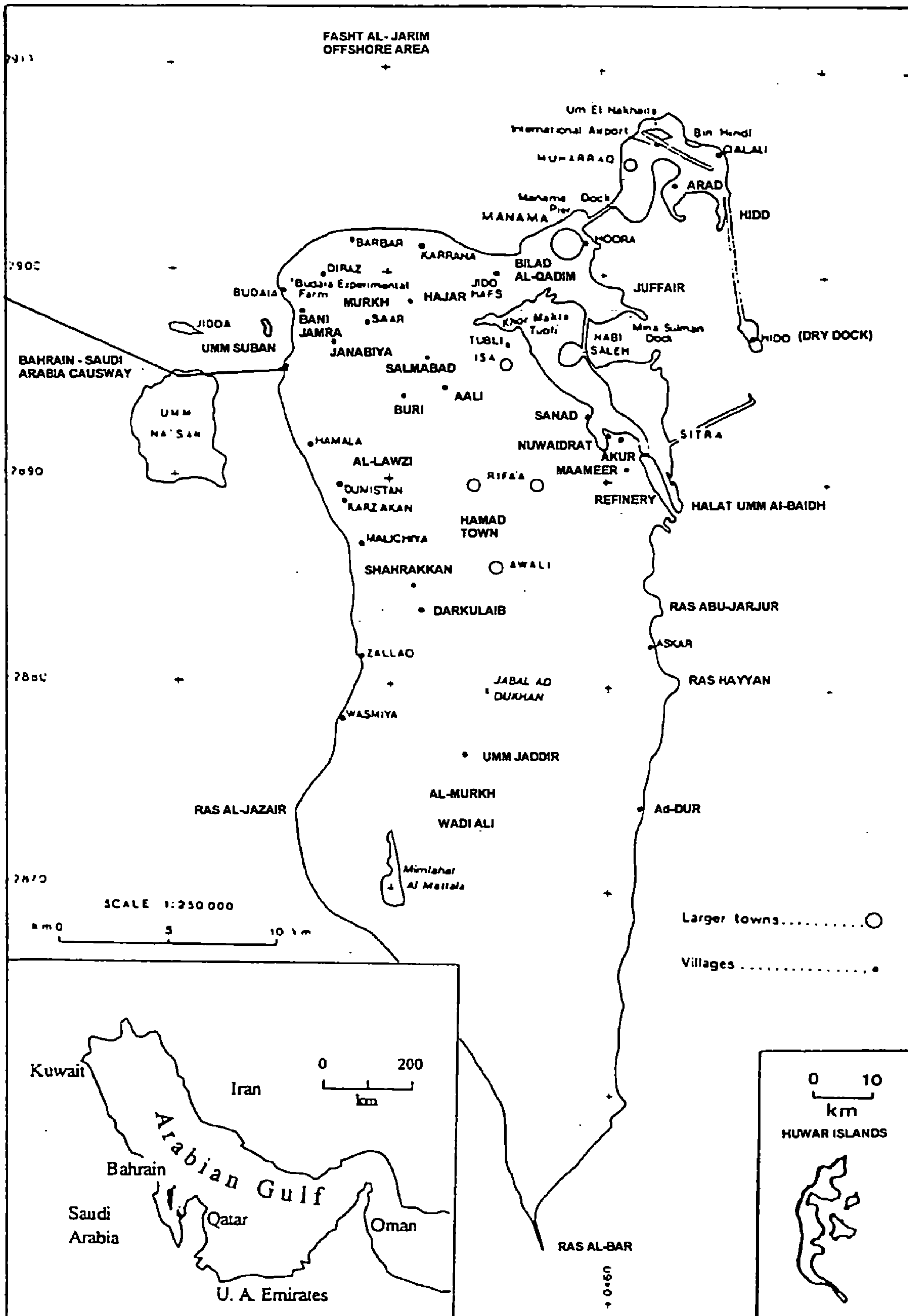
CHAPTER TWO
PHYSICAL CONDITIONS

2.1 The Study Area

Bahrain is an archipelago consisting of thirty three low-lying islands, situated in a shallow bay of the Arabian Gulf known as the Gulf of Salwa, approximately halfway between the eastern coast of Saudi Arabia to the west and the northern coast of the Qatar Peninsula to the east (approximately latitude 25° 32′ and 26° 20′ North, and longitude 50° 20′ and 50° 50′ East). The location of the study area is shown in Figure 2.1. These islands occur in two unequal-sized groups; namely, the Bahrain Islands group, and Huwar Islands group; with a total area of about 710.9 km^2 and a population of 650,604 inhabitants (CSO, 2002). This gives a population density of about 916 inhabitants/km^2, which is one of the most densely populated countries in the world.

The larger group includes Bahrain Island itself, Muharraq Island to the northeastern coast, and Sitra Island - just off the eastern coast of the main island. The other important islands are Umm Nassan, Nabih Saleh, Jiddah, and Umm As-Suban Islands (Figure 2.1). The largest and most important island in this group is the Bahrain Island itself, which accounts for more than 84% of the country's total area, and accommodates the major commercial and urban centres. It has an elongated shape of about 50 km from north to south and from 12 – 18 km from east to west. Both Muharraq and Sitra Islands are connected to the main island by short causeways, and since 1986, the main island is linked to the Saudi Arabia mainland through a 25 km long causeway (The King Fahad Causway) that also connects it

Figure 2.1 The location of the study area (inset map shows its regional location)



with the northern tip of the Umm Nassan Island to the west. This group also includes numerous islets, which are merely shoals and patches of coral reef and some of them are covered by seawater during high tides.

The Huwar Islands group lies further off the southeastern coast of the main island adjacent to the northwestern coast of Qatar Peninsula (Figure 2.1). This group also forms a north-south oriented archipelago, with a total area of approximately 17 km^2. The largest island in this group is the Huwar Island itself, which also has an elongated shape, extends for 26 km and attains a width of 4.4 km at its widest point. Huwar Island is surrounded by smaller flat-lying islands, including Suwad As Shamaliyah, Sawad Al-Janubiyah Rabad As Sharqiyah, and Muhazwara.

2.2 Climate

The climate of Bahrain Islands is typical of arid and semi-arid zones, where the mean evaporation considerably exceeds rainfall. However, this supposedly dry weather is modified under the influence of the surrounding sea to produce high humidity levels throughout the year. The Bahrain climate is characterised by low rainfall, high relative humidity, high temperature, relatively low evaporation rates, and the domination of the north-westerly winds. The climatic year can be divided into two periods, separated by two transitional ones. The summer period (June – September) is normally hot and humid, while the winter (December – March) is mild with some scanty rainfall. The transitional periods are (April – May) and (October – November), and are characterised by somewhat moderate weather. Although these are normally referred to as the spring and autumn transitions, respectively, autumn and spring seasons are not clearly defined in terms of significant weather variations.

The mean value of relative humidity is 66 %; this includes monthly means ranging from 74 % in January to 59 % in May and June. Temperatures are high, with monthly means ranging from 17.2°C in January to 34.2°C in August. Rainfall is low, erratic and variable and it mainly occurs in form of short duration rainstorms, with an annual average of about 78 mm. The monthly means of potential evaporation vary from 89 mm in January to 280 mm in June; the calculated daily average is 5.75 mm. Prevailing winds are of northwest direction, and mean daily wind speed is about 9.5 knots. Mean monthly sunshine hours range from 7.3 to 11.3 hours per day in January and June, respectively. Annual average atmospheric pressure is approximately 1,010 hpa. Monthly mean sea temperature varies from 17°C in February to 33°C in August. The average number of days per year that visibility is reduced to one kilometre or less by fog is 6.6 days, and by dust haze is 4.5 days, with January and July representing the highest monthly fog and dust haze at 1.7 and 1.1 days, respectively. The medium-to long-term climatological means are summarised in Table 2.1, whilst the relation between the monthly mean temperatures, rainfalls, relative humidity, and evaporation is expressed diagrammatically in Figure 2.2.

Substantial climatic data were made available from different meteorological stations; but most of these stations provided short, irregular, and, in many cases, unreliable records. An important exception to this generalisation is the Bahrain International Airport Station where moderately reliable medium to long-term meteorological data (some of which date back to 1931) exist. The Agricultural Authority keeps climatological records at Budaiya Experimental Garden on temperature, relative humidity, rainfall, evaporation, winds, and

Table 2.1 The medium to long-term climatological means at Bahrain International Airport 1960 – 1999

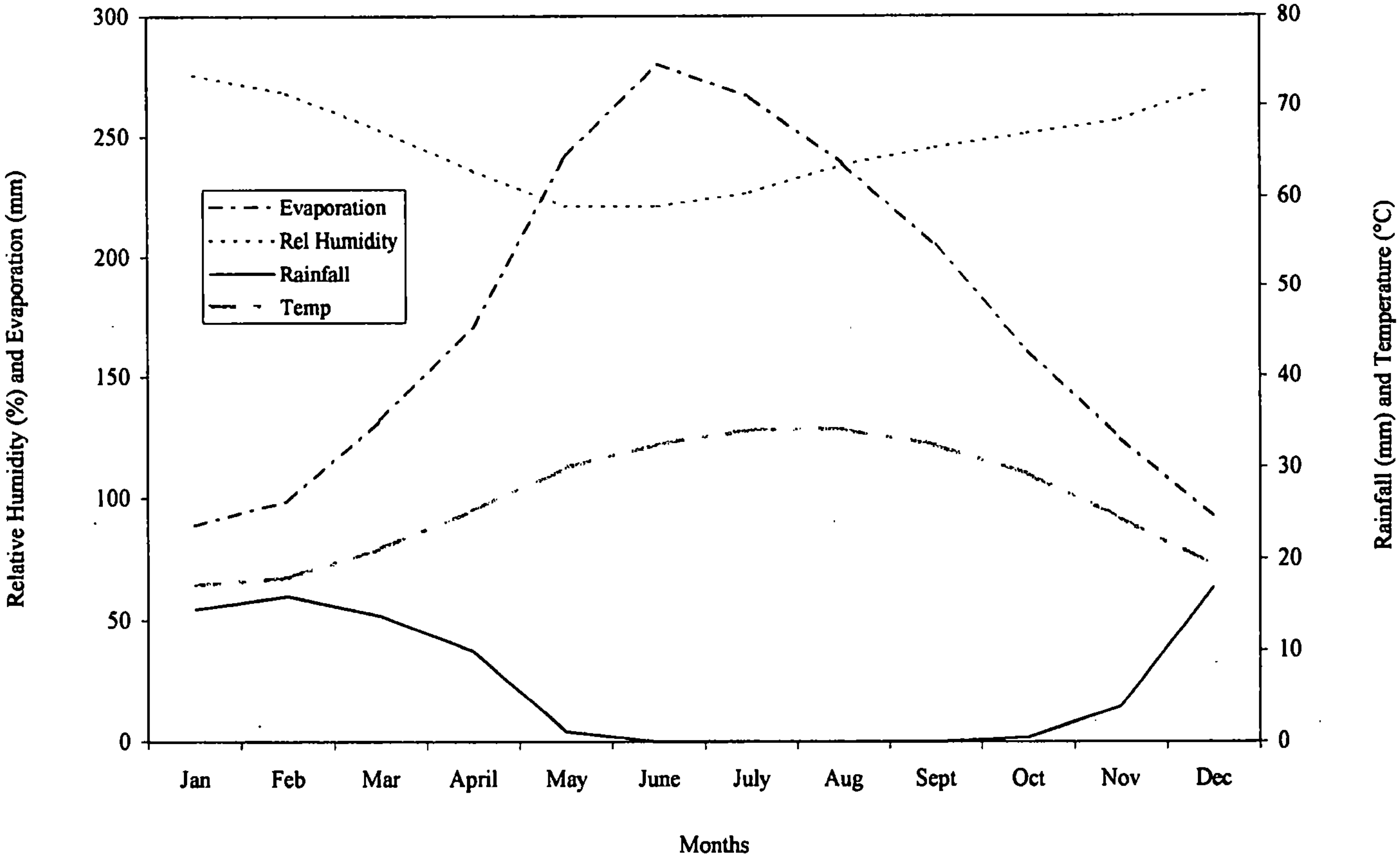
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean temperature (°C)	17.2	18.0	21.2	25.3	30.0	32.6	34.1	34.2	32.5	29.3	24.5	19.3
Mean daily max. temp. (°C)	20.0	21.2	24.7	29.2	34.1	36.4	37.9	38.0	36.5	33.1	27.8	22.3
Mean daily min. temp. (°C)	14.1	14.9	17.8	21.5	26.0	28.8	30.4	30.5	28.6	25.5	21.2	16.2
Mean daily max. rel. hum. (%)	88.0	88.0	85.0	82.0	79.0	78.0	80.0	83.0	86.0	88.0	85.0	87.0
Mean daily min. rel. hum. (%)	59.0	55.0	50.0	44.0	39.0	40.0	41.0	44.0	45.0	46.0	52.0	57.0
Mean daily M.S.L pressure (hpa)	1019	1017	1014	1011	1007	1001	998	999	1005	1012	1017	1019
Mean daily vap. pressure (hpa)	14.8	15.2	16.9	20.1	25.0	27.9	31.8	34.4	32.1	27.3	21.6	16.9
Prevailing wind direction	NW	NNW	NNW	N	NNW	NW	NW	NW	NNW	NNW	NNW	NW
Mean daily wind speed (Knots)	10.3	10.7	10.0	9.2	9.6	11.0	8.4	8.5	7.2	7.8	8.9	9.7
Mean evaporation (mm)	89.0	99.0	131.9	170.5	241.7	280.1	266.3	239.0	204.5	160.2	124.2	92.5
Mean daily hours of sunshine (h/day)	7.3	7.9	7.7	8.5	9.9	11.3	10.7	10.7	10.4	9.8	8.7	7.3
Mean total precipitation (mm)	14.6	16.0	13.9	10.0	1.1	Nil	Nil	Nil	Nil	0.5	3.8	10.9
Mean number of rain days (> 1mm)	2.0	1.9	1.9	1.4	0.2	Nil	Nil	Nil	Nil	0.1	0.7	1.7
Mean number of days per month with:												
Fog (visibility 1 km or less)	1.7	1.2	0.4	*	0.2	0.1	0.1	*	0.3	0.7	0.9	1.0
Dust (visibility 1km or less)	0.2	0.3	0.5	0.6	0.2	0.8	1.1	0.3	0.1	0.1	0.1	0.2
Thunderstorms	1.1	0.9	1.7	1.9	0.6	Nil	Nil	Nil	Nil	0.2	0.6	0.8

Notes:

SOURCE: Meteorological Services

1- (*) Less than 0.05 but more than zero.
2- Prevailing wind 1973 – 1999.
3- Wind speed 1980 – 1999.
4- Sunshine hours 1968 – 1999.
5- Evaporation 1983 – 1999.
6- Mean daily vap. pressure values rounded to the nearest decimal point. 7- Table entries for M.S.L. pressure have been numerically rounded for presentation.

Figure 2.2 The relation between the main climatic parameters



sunshine hours. Although it contains some abnormalities, the first set of these data (1970 through 1979) of this station is relatively reliable; the recent records, however, appear to be less accurate plus containing several gaps.

Bahrain Refinery and Awali Authority were collecting limited meteorological data, but these records were discontinued in 1983 (A. Al-Qaraan, Bahrain Refinery, personal communication). The United States Navy also keeps records on relative humidity, temperature, and wind speed as part of their navigation requirements, but these data were not made available for this research for processing and interpretation. One year's observations (1978 – 1979), with the measurement of air and soil temperatures, relative humidity and evaporation were obtained from Umm Nakhila Station. The recent meteorological station established in 1991 at Sheikh Isa Air Base produces reliable records on temperature, relative humidity, and wind speeds. More recently, in 1997, meteorological facilities were established at Howrat Aali Agricultural Project to measure air and soil temperature, rainfall, and relative humidity. Climatic records from this station were, however, discontinued in 1998 due to technical problems. The locations of the existing and abandoned climatological points are shown in Figure 2.3, and their climatic parameters and length of records are given in Table 2.2.

Because of its relatively long-term and reliable records, the meteorological facilities at Bahrain International Airport will be considered more representative, and most of the previous and following discussion is based on data provided by the airport authority. For the purpose of investigating possible micro-climate modifications around Bahrain, these data were compared with the first set of records at Budaiya Station and the observational data obtained from Sheikh Isa Air Base, which were considered of adequate quality.

Figure 2.3 The locations of the existing and abandoned climatic stations

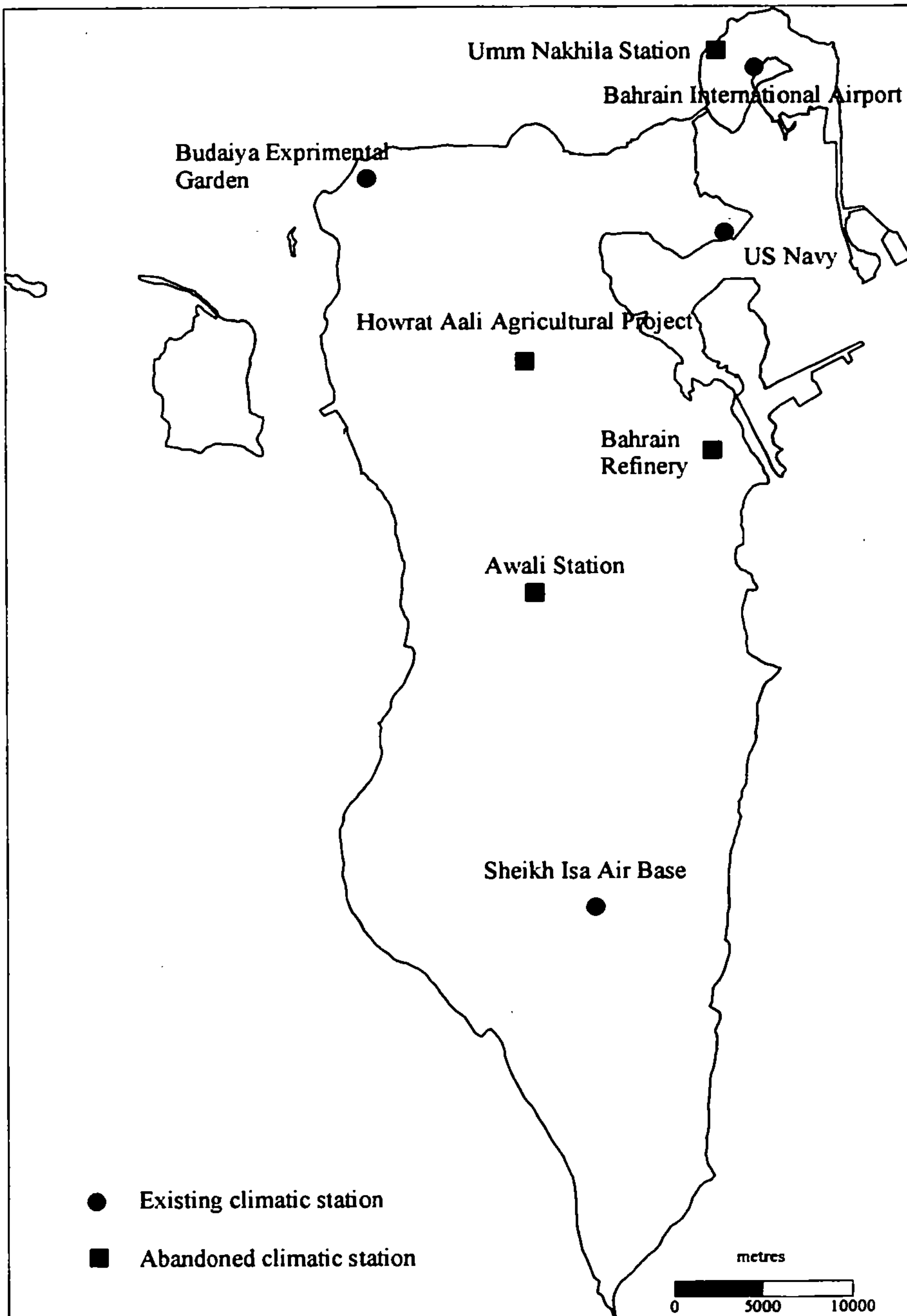


Table 2.2 The existing and abandoned climatic stations in Bahrain and their period of records

Climatic Station	Airport	Budaiya	Refinery	Awali	Umm-Nakhila	US Navy	Sheikh Isa Air Base	Howrat A'ali
Temperature	1948 – Pres.	1970 – Pres.	1960 – 1969	1976 – 1984	1978 – 1979	1978 – ?? 1993 – 97	1991 – Pres.	1997 – 1998
Rainfall	1902 – Pres.	1974 – Pres.	1960 – 1984	---	---	---	---	1997 – 1998
Relative humidity	1964 – Pres.	1974 – Pres.	1960 – 1969	1976 – 1984	1978 – 1979	1978 – ?? 1993 – 97	1991 – Pres.	1997 – 1998
Evaporation	1983 – Pres.	1970 – Pres.	---	---	---	---	---	1998 – 1998
Wind speed	1968 – Pres.	1974 – Pres.	---	Not known	---	---	1991 – Pres.	---
Sunshine	1968 – Pres.	1970 – Pres.	---	---	---	---	---	---
Soil temperature	---	---	---	---	1978 – 1979	---	---	1997 – 1998
Atmospheric pressure	1931 – Pres.	---	---	Not known	---	---	---	---
Vapour pressure	1931 – Pres.	---	---	---	---	---	---	---
Visibility	1946 – Pres.	---	---	---	---	---	---	---

SOURCE: Adapted and updated after GDC (1979b).

Notes:
(1) Budaiya record contains several gaps, with also gaps in particular parameters.
(2) US Navy records re-initiated in 1993. The end of the first period of record is not known.
(3) Temperature & Relative humidity periods of record at Awali obtained by personal communication.
(4) A dash indicates parameter not recorded. Pres. = Present.

Short-term data acquired from the existing and abandoned minor stations will only be referred to complete the climatic picture.

In broad terms, the micro-climatic analysis shows slight weather modifications when departure from densely vegetated to desert conditions exists; for example, where sheltered conditions prevail, the relative humidity tends to be higher. On the contrary, the average wind speeds are greater in the desert dominant areas than in the sheltered places. The analysis also reveals that the open places are relatively cooler and experience greater evaporation rates. Rainfall variability and density are homogenous, although localised rainstorms may somewhat alter this pattern of rainfall distribution.

Temperature

Temperatures are generally high; the mean value at Bahrain International Airport is about 26.5°C. This varies from a mean daily minimum of 14.1°C in January to a mean daily maximum of 38°C in August. The highest temperature so far recorded was 46.7 °C in July 1972 and the lowest was 2.7°C in January 1964. The mean daily maximum, mean daily minimum, highest and lowest monthly temperatures, and the monthly means are given in Table 2.3.

Climatic data on the maximum and minimum temperatures have been recorded at Bahrain International Airport since 1948. For the purpose of comparison, these data were used to calculate the average monthly means for the period 1969 – 1980 (Table 2.4). Table 2.5 shows the monthly mean temperatures at Budaiya Station for the same period. It can be inferred from the tables that airport record shows values higher than those of Budaiya, of the order of 1 – 3 °C. Similarly, the one-year record at Umm Nakhila Station (partially vegetated area) shows temperatures cooler than those in the airport by at least 1 °C. This clearly indicates temperature modification as a result of sheltered and vegetationally covered locations (Oasis effects as termed by Wright and Ayub, 1973).

Table 2.3 Temperatures, mean values and highest and lowest recorded

Months	Temperature records (° C)				
	Mean daily maximum	Mean daily minimum	Monthly mean	Highest recorded	Lowest recorded
January	20	14.1	17.2	31.7	2.7
February	21.2	14.9	18.0	34.7	7.9
March	24.7	17.8	21.2	38.1	7.8
April	29.2	21.5	25.3	41.7	14.2
May	34.1	26.0	30.0	46.7	18.7
June	36.4	28.8	32.6	45.7	22.7
July	37.9	30.4	34.1	45.6	25.2
August	38.0	30.5	34.2	45.7	26.0
September	36.5	28.6	32.5	42.8	23.5
October	33.1	25.5	29.3	41.4	18.5
November	27.8	21.2	24.5	35.0	13.5
December	22.3	16.2	19.3	29.4	6.4

SOURCE: Meteorological Services.

The Sheikh Isa Air Base records, being influenced by the desert conditions, have larger temperature range throughout the year than that at Bahrain Airport (Meteorological Services, 1995). Table 2.6 gives the means monthly temperature at Sheikh Isa Air Base during the period 1991 – 1997 compared with the corresponding means at airport. The mean maximum temperature at Sheikh Isa Air Base has been found to be always

Table 2.4 Monthly mean temperatures at Bahrain International Airport 1969 – 1980

Months	Monthly mean temperatures (° C)												Average monthly means
	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	
January	18.5	18.2	17.4	16.9	15.7	16.4	17.6	18.0	15.4	19.7	19.4	17.8	17.6
February	21.5	19.8	18.5	18.3	22.8	19.3	18.0	18.5	18.7	20.8	20.9	19.0	19.7
March	27.0	24.0	22.4	20.1	23.7	23.4	21.9	18.5	24.0	22.6	23.2	23.4	22.9
April	28.0	28.9	26.8	24.5	29.4	27.5	26.3	26.5	26.9	28.3	27.6	27.8	27.4
May	31.9	30.9	30.4	34.0	32.1	31.2	31.5	32.3	31.1	30.7	31.3	32.2	31.6
June	32.2	31.5	33.6	32.9	33.3	34.0	32.8	33.4	35.1	34.1	37.2	35.8	33.8
July	33.8	35.8	34.1	34.2	34.9	36.2	36.3	33.3	35.7	35.8	35.8	36.5	35.2
August	34.7	34.1	33.6	35.7	35.0	35.2	34.0	33.6	35.6	34.6	35.1	35.4	34.7
September	33.0	31.3	32.8	32.7	33.3	34.2	34.6	32.7	32.9	32.2	34.4	34.4	33.2
October	31.6	28.5	28.6	30.0	29.9	29.0	27.6	30.5	29.6	29.9	30.5	30.1	29.7
November	24.4	25.6	24.5	25.8	25.0	29.1	23.1	24.5	24.8	23.7	23.8	24.6	24.9
December	20.9	18.7	17.9	17.2	17.9	18.4	19.1	20.8	20.4	21.3	18.6	18.8	19.2

SOURCE: Calculated from the maximum and minimum temperature data provided by the Meteorological Services.

Table 2.5 Monthly mean temperatures at Budaiya and corresponding averages at airport 1969 – 1980

Month	Monthly mean temperatures (° C)												Average monthly means	Corresponding average at airport
	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980		
January	17.1	17.3	16.5	15.0	---	16.1	16.8	16.1	14.8	16.9	17.1	22.5	16.9	17.8
February	15.5	18.0	17.0	15.1	---	17.4	17.5	16.2	17.0	17.6	19.3	21.3	17.4	19.4
March	23.6	21.4	20.8	20.2	---	21.5	20.9	20.9	21.5	20.2	20.5	23.6	21.4	22.8
April	23.4	26.5	23.3	24.2	---	25.8	24.9	23.3	24.0	25.2	25.3	27.7	24.9	27.2
May	27.7	28.1	29.5	27.8	---	29.3	30.0	28.2	29.0	27.7	28.6	29.3	28.7	31.6
June	30.3	30.2	30.1	32.0	---	32.1	32.2	29.1	31.0	29.5	32.7	32.5	31.1	33.9
July	31.8	32.9	32.5	32.0	---	33.5	32.3	31.6	31.5	32.5	34.3	38.3	33.0	35.2
August	31.8	32.0	32.8	32.9	---	33.9	32.8	31.4	32.5	31.1	36.0	36.5	33.1	34.7
September	29.5	29.8	30.6	30.7	---	31.8	32.8	29.5	30.5	30.0	36.1	37.4	31.7	33.2
October	28.9	26.5	26.8	27.4	---	27.7	30.3	29.4	28.0	26.8	29.6	38.9	29.1	29.6
November	23.0	23.6	23.2	23.6	---	23.6	22.2	23.1	20.5	21.8	27.8	25.0	23.4	24.4
December	19.8	18.0	17.5	16.1	---	19.5	18.7	19.1	19.8	19.8	21.7	21.5	19.2	19.3

SOURCE: Compiled, adapted and calculated from data made available by Agricultural Affairs and Meteorological Services.

Notes: [1] No records were kept for 1973.
[2] Average means are rounded to the nearest decimal point.

Table 2.6 Monthly mean temperatures at Sheikh Isa Air Base and corresponding averages at airport 1991 – 1997

Year	Monthly mean temperatures (°C)											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1991	---	---	---	---	---	---	---	---	---	---	22.1	18.8
1992	13.1	15.1	16.9	23.4	29.9	33.9	33.6	34.0	31.5	26.7	22.9	17.5
1993	14.5	16.1	20.3	24.2	29.7	32.7	34.4	34.4	31.5	28.8	22.7	18.3
1994	17.4	16.8	20.2	---	30.7	33.5	35.1	33.4	32.0	28.5	25.0	16.7
1995	16.1	17.4	19.6	24.1	30.0	33.5	33.9	33.7	31.1	27.8	22.3	17.0
1996	16.0	---	20.1	24.9	31.1	32.9	35.4	34.7	32.0	27.9	22.2	19.0
1997	16.7	16.1	18.2	23.0	30.3	33.5	34.9	33.9	32.1	28.9	22.3	18.1
Average monthly means	15.6	16.3	19.2	23.9	30.3	33.3	34.6	34.0	31.7	28.1	22.8	17.9
Corresponing avergs. at airport	17.2	18.7	20.9	26.4	31.9	34.5	34.8	35.4	32.6	29.7	24.3	19.5

SOURCE: Modified after Meteorological Services, 1995.
A dash indicates no record.

higher than at the airport, while the mean minimum is always lower. For instance, at extremes, the July mean daily temperature at Sheikh Isa exceeds Bahrain Airport by 4°C, whereas the December and January mean daily temperatures are nearly 2°C lower at the former station (Meteorological Services, 1995). This may suggest that the weather is generally cooler in the south of Bahrain where desert condition is predominant.

Furthermore, GDC (1980a) have processed the nine-year temperature record (1960 – 1969) of Bahrain Refinery and found that temperature values at refinery are slightly higher than Bahrain International Airport during the summer months, which possibly suggests temperature adjustment attributed to variation in humidity level and difference in elevation.

Rainfall

Rainfall in Bahrain is low, variable and irregular, and mainly occurs in the form of short duration heavy thunderstorms, which can be relatively spatially variable. These storms are classified, according to Isa (1989), into two types: conventional and frontal rainstorms. The conventional rainfall is resulted from the passage of warm-air over the surface of the Arabian Peninsula that, when forced up, become cold to form heavy clouds (Cumulo Nimbus) (Abdulmajeed Isa, Meteorological Services, personal communication). The frontal rainfall is normally caused by the development of atmospheric depressions and cold fronts associated with the easterly winds blown from the Indian Ocean. In spite of being rare, thunderstorms usually produce flash floods and run-off that often results in severe road and urban flooding, and sometimes damage agricultural land. Elagib and Abdu (1997) observe that the runoff patterns in Bahrain reflect the rainfall variability, and even with daily amounts of rainfall higher than the average, runoff is affected by local conditions such as soil characteristics, local topography, rainfall density, and time of occurrence.

The amounts of rainfall are insufficient neither for recharging the underground aquifers nor for rain fed irrigation; only the most drought-resistant vegetation can survive. Further to the south and southwest of the main island, however, filling of wadis and marginal depressions occurs to develop playa lakes in enclosed basins, because of the relatively low infiltration rates (Doonrkamp *et al.*, 1980). A small amount of this rainwater percolates into the exposed part of the underground aquifer to form shallow and limited fresh water lenses of perched water floating above brackish groundwater.

Analysis of the rainfall record at Bahrain International Airport suggests an annual average rainfall of 78 mm, but this figure includes a wide annual range from 1.6 mm in 1946 to 226.8 mm in 1976. Most of the rainfall occurs in winter months between December and February, and exhibits wide variability in terms of monthly means. The highest average being recorded in February at 16.0 mm, while the driest month is October with only 0.3 mm. The months of June, July, August and September recorded nil precipitation (Table 2.1). The highest daily and monthly rainfalls were both recorded in March 1995 at 67.9 and 139.2 mm, respectively. The highest mean number of days of thunderstorms occurs in April (1.9 days), and the lowest occurs in October (0.2 day). The monthly rainfall and means at Bahrain International Airport for the period 1902 - 1997 are given in Table A-1, Appendix A. Analysis of rainfall data also indicates that rainfall in Bahrain seems to have cyclic pattern of wet and dry periods roughly every seven years (Zubari *et al.*, 1996). The monthly and annual rainfall probabilities for various return periods are presented in Table 2.7.

Table 2.7 Monthly and annual rainfall probabilities (mm of rainfall met or exceeded)

Annual probability	20%	10%	6.6%	5%	2%	N*
Return period	5yr	10yr	15yr	20yr	50yr	Years
January	27.7	55.1	71.6	85.6	-	41
February	23.6	56.7	69.0	79.8	102.0	60
March	20.4	41.2	44.2	55.2	71.5	60
April	13.8	49.4	53.1	61.6	-	28
May	2.5	4.8	9.4	10.1	-	41
October	0.1	1.8	3.9	6.5	-	27
November	7.3	13.3	18.5	44.7	129.2	59
December	11.8	36.8	59.9	79.1	-	27
Annual prob.	111.5	161.1	167.9	169.2	-	59

SOURCE: Meteorological Services.
*Indicates number of years used in the analysis.

The short-term (1974 – 1980) annual average rainfall at Budaiya Station is 82 mm, while the corresponding average at the airport is 89.8 mm (Table 2.8). However, some of these data seem anomalous and should be interpreted with caution. For instance, the months of January and February 1980 at airport recorded 31.2 and 57.1 mm, respectively, whilst Budaiya recorded nil precipitation. Comparatively, Budaiya recorded 74.5 mm in March 1976 and 27.5 mm in May 1977, whereas the values for those months at the airport were 1.7 and 9.2 mm, respectively. Although these observations appear suspicious, they may suggest occurrence of localised thunderstorms.

The 1968 – 1975 rainfall data recorded at the Refinery Climatic Station were analysed by (GDC, 1980a) and the resulting annual average was compared with the corresponding average at airport. This has shown rainfall annual averages of 73.4 mm and 70.6 mm at

Table 2.8 Monthly mean rainfalls at Budaiya and corresponding averages at Airport 1974 – 1980

Month	Monthly mean rainfalls (mm)							Average monthly means	Corresponding averages at airport
	1974	1975	1976	1977	1978	1979	1980		
January	4.0	22.5	14.0	61.0	2.0	8.5	--	16.0	20.8
February	5.0	7.2	81.5	TR	6.0	2.0	--	14.6	21.6
March	31.5	33.1	74.5	5.5	4.5	1.0	4.5	22.1	17.1
April	1.5	3.1	41.0	7.5	--	--	3.0	8.0	8.8
May	--	--	0.3	27.5	1.5	--	--	4.2	1.3
June	--	--	--	--	--	--	--	--	--
July	--	--	--	--	--	--	--	--	--
August	--	--	--	--	--	--	--	--	--
September	--	--	--	--	--	--	--	--	--
October	--	--	--	1.3	--	--	--	0.19	0.19
November	--	--	--	1.5	4.5	--	--	0.86	1.1
December	80.4	9.5	14.0	7.0	--	2.0	--	16.1	18.9
Annual Averages								82.0	89.9

SOURCE: Adapted and calculated from the Agricultural Affairs and Meteorological Services records.
Notes: [1] A dash indicates nil rainfall.
[2] TR = traces.

the refinery and airport, respectively. Although, not proven quantitatively, Isa (1989) believes that the southern parts of the study area receive more rainfall. The aforementioned comparisons, are nevertheless, indicate that apart from some localised rainstorms, one could assume that rainfall in Bahrain is generally homogenous, and is fairly evenly distributed throughout the study area.

At this point it is only to be mentioned that in order to provide more reliable analysis of rainfall distribution in the study area, the meteorological facilities at Sheikh Isa Air Base Station should be expanded to include rainfall measurement. Installation of reliable weather monitoring, including rainfall, in Huwar Islands should also be considered.

Evaporation

Evaporation rates range from about 2.87 mm per day in January to about 9.33 mm per day in June; giving a daily average of 5.75 mm. Table 2.9 presents the monthly evaporation rates and means for the year 1983 – 1997 at Bahrain International Airport. The monthly evaporation means at Budaiya Station for the period 1970 – 1980 are summarised in Table 2.10. Unfortunately, analysis of corresponding averages was not possible, because the airport record was started only in 1983. Nevertheless, the short-term Budaiya data were correlated with the medium-term record of the airport, and the correlation shows an annual average difference of between 10 – 34 % between the two stations. Generally, the Budaiya average is about 23 % lower than that of the airport.

The annual evaporation rates, as shown in Table 2.10, are 2,099 mm at the airport and 1,615 mm at Budaiya. This lower evaporation rate clearly reflects the protected condition

Table 2.9 Totals monthly evaporation and means at Bahrain International Airport 1983 -1997

Year	Total and monthly means evaporation (mm)											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1983	72.9	81.3	127.8	161.6	218.4	269.9	260.3	238.5	192.2	143.9	90.7	81.0
1984	51.8	85.6	126.3	184.2	204.9	251.0	236.9	239.8	174.6	135.4	76.5	65.5
1985	57.3	94.7	116.5	145.9	162.8	214.9	189.3	186.0	170.7	144.2	102.1	67.4
1986	93.9	117.3	166.2	185.1	317.7	391.0	334.4	275.3	258.6	209.2	173.2	142.2
1987	133.2	126.8	149.5	171.6	199.1	211.7	252.2	---	207.4	152.7	119.0	97.9
1988	91.1	81.4	126.8	173.2	278.3	288.9	277.2	253.5	194.9	158.2	106.9	85.6
1989	113.1	88.3	105.5	125.9	231.7	271.3	203.4	179.0	170.3	145.1	119.6	81.4
1990	88.5	93.5	131.1	175.3	246.0	247.4	238.1	234.4	196.0	151.0	111.8	105.5
1991	78.6	86.3	99.6	152.9	196.4	234.7	230.5	189.3	176.0	139.0	126.5	78.5
1992	93.6	103.8	134.7	158.9	223.8	276.5	274.1	228.8	193.2	140.6	117.4	---
1993	63.0	68.9	160.5	163.1	256.9	317.9	278.4	266.5	207.0	172.0	158.9	88.4
1994	100.2	127.5	153.4	191.3	282.8	305.8	317.3	288.8	221.1	180.0	146.2	132.2
1995	100.7	100.6	123.6	219.9	309.7	357.8	361.0	278.4	272.1	193.9	154.5	77.5
1996	101.3	89.1	124.7	177.6	255.7	283.2	275.6	249.0	228.2	177.9	135.2	99.9
1997	96.2	139.5	83.8	195.7	270.1	342.3	360.0	400.5	285.9	209.3	95.8	103.1
Averages monthly means	89.0	99.0	131.9	170.5	241.7	280.1	266.3	239.0	204.5	160.2	124.2	92.5

SOURCE: Modified after data made available from Meteorological Services.
A dash indicates no records.

Table 2.10 Monthly means evaporation (Class A – Pan) at Budaiya and corresponding average at airport 1970 – 1980

Months	Monthly means evaporation (mm)										Average monthly means	Correspon. averages at airport
	1970	1971	1972	1974	1975	1976	1977	1978	1979	1980		
January	---	76.0	65.0	58.9	56.7	68.2	77.5	77.5	93.0	111.6	76.0	89.0
February	---	125	100.0	78.3	67.2	53.2	70.0	78.3	89.6	92.8	83.8	99.0
March	---	186	87.0	127.1	128.9	71.3	77.5	80.6	99.2	139.5	110.8	131.9
April	264	158	140	195	132	93.0	40.0	78.0	96.0	120.0	136.6	170.5
May	300	254	242	210.8	201.5	96.1	108.5	80.6	96.1	133.3	172.3	241.5
June	274	268	276	225	207	150	105.0	69.0	111.0	159.0	184.4	280.1
July	292	278	305	254.2	193.1	158.1	77.5	108.5	102.3	232.5	200.1	266.3
August	---	260	240	220.1	207.7	139.5	93.0	108.5	96.1	186.0	172.3	239.0
September	201	193	248	183.0	168	129.0	90.0	105.0	114.0	177.0	160.8	204.5
October	177	167	139	133.3	145.7	111.6	62.0	105.4	151.9	133.3	132.6	160.0
November	120	59.0	118	90.0	99.0	96.0	75.0	93.0	159.0	114.0	102.3	124.2
December	108	88.0	58.0	62.0	71.3	96.1	62.0	102.3	105.4	74.4	82.8	92.5
Annual averages											1615	2099

SOURCE: Modified after Destane and Ayub, 1979 and based on data made available from the Agriculture Affairs.

Notes: [1] No records were kept for 1973.

[2] Average means are rounded to the nearest decimal points.

[3] A dash indicates no record.

at Budaiya. Table 2.11 gives recent record at Budaiya that shows evaporation rates between 1 to 11 % lower than the common ones at the airport. It is interesting to note that the evaporation class-A Pan equipment at Budaiya has been moved from its previous sheltered place to a relatively open area within the same location since 1984.

Relative Humidity

Because of its maritime location, the weather in Bahrain is very humid. In fact, the high seawater temperatures of the Arabian Gulf and the development of temperature inversions result in generally high humidity levels throughout the year (Doornkamp *et al.*, 1980). Mean daily maximum humidity is about 84 %, while the mean daily minimum is 48 %. The humidity values drop to about 42 % in response to high temperatures during the summer months; but increases to about 74 % in January.

Humidity is also sensitive to wind directions and magnitudes; for examples, the high-speed shamal winds tend to reduce humidity levels, whilst the south-easterly generally low-speed winds create humid conditions. A more spectacular effect, although less frequent, results from the high south westerly continental winds that, having been travelled over the hot and dry Arabian landmass, produce very sudden drops in humidity (GDC, 1980a).

The mean monthly relative humidity at Bahrain International Airport for the period 1963 – 1997 is tabulated in Table A-2 of Appendix A, whilst Table 2.12 gives the mean monthly relative humidity at Budaiya for the period 1974 - 1980 compared with those of the corresponding period at airport. The later table demonstrates that Budaiya relative humidity exceeds that at airport by up to 10 %, and that the annual average relative humidity at airport for the corresponding period exactly reflects the long-term average

Table 2.11 Monthly means evaporation at Budaiya for the periods 1983 – 1986 and 1994 – 1997 and corresponding averages at airport (mm)

Months	Monthly evaporation 1983 - 1986				Average monthly means	Correspon. averages at airport	Monthly evaporation 1994 - 1997				Average monthly means	Correspon. averages at airport
	1983	1984	1985	1986			1994	1995	1996	1997		
January	75.0	71.3	80.6	62.0	72.2	69.0	117.8	108.5	96.1	42.7	91.3	99.6
February	54.0	84.1	131.6	70.0	85.0	95.0	133.4	100.8	86.8	113.0	108.5	114.2
March	97.0	127.1	158.1	105.4	121.9	134.2	151.9	124.0	127.1	108.1	127.8	121.4
April	107.0	180.0	216.0	126.0	157.2	169.2	195.0	219.0	192.0	184.8	197.7	196.1
May	201.0	210.8	254.2	124.0	197.5	226.0	275.9	310.0	235.6	236.8	264.6	272.1
June	95.0	285.0	294.0	180.0	213.7	281.7	315.0	372.0	282.0	256.1	306.3	322.3
July	242.0	235.6	272.8	217.0	241.9	255.2	310.0	359.6	275.9	279.8	306.3	328.5
August	242.0	291.4	279.0	208.9	255.3	234.9	288.3	279.0	248.0	---	271.8	239.2
September	135.0	324.0	234.0	189.0	220.5	199.0	222.0	264.0	228.0	190.7	226.2	251.9
October	147.0	220.1	204.6	124.0	174.0	158.2	195.3	201.5	198.4	141.4	184.2	176.8
November	102.0	138.0	135.0	75.0	112.5	110.6	150.0	159.0	135.0	61.2	126.3	133.0
December	83.0	102.3	89.0	58.0	83.1	89.0	142.6	71.3	89.9	65.4	92.3	103.2

SOURCE: Compiled and calculated from records made available from Agricultural Affairs and Meteorological Services.
A dash indicates no record.

Table 2.12 Comparison between monthly mean relative humidity at Budaiya and Bahrain International Airport 1974 – 1980

Months	Relative humidity at Budaiya Station (%)							Relative humidity at Bahrain International Airport (%)						
	1974	1975	1976	1977	1978	1979	1980	1974	1975	1976	1977	1978	1979	1980
January	76.7	79.9	79.1	78.5	78.1	79.1	80.0	73	76	79	74	71	71	75
February	75.8	77.8	76.1	76.8	76.4	80.5	79.6	70	74	75	76	75	71	76
March	76.3	69.9	78.0	72.5	68.5	80.9	76.2	65	63	73	66	65	64	64
April	64.8	71.3	74.0	68.8	69.2	81.7	73.1	61	63	69	61	56	59	61
May	71.4	61.6	59.9	70.0	69.3	79.4	71.7	63	58	59	60	57	63	59
June	69.0	54.2	69.4	70.6	68.9	81.2	59.1	59	61	61	58	57	59	60
July	68.9	62.1	70.6	68.5	73.1	85.2	67.5	62	65	59	58	65	62	62
August	71.1	64.7	72.9	75.0	75.0	84.1	30.7	65	63	68	65	61	65	65
September	74.2	68.1	73.8	75.5	73.4	84.9	78.2	65	65	67	67	65	65	66
October	74.4	70.0	71.1	75.0	73.5	92.5	63.0	65	67	65	67	69	70	68
November	76.5	73.6	75.1	77.0	78.7	29.0	77.5	69	69	69	70	69	69	68
December	80.5	77.4	79.1	75.0	77.8	77.4	70.6	76	73	75	72	60	73	71
Aver. means (%)				72.8							66.0			

SOURCE: Compiled and calculated from data made available from Agricultural Affairs and Meteorological Services.

(Table 2.1). These observations once again emphasise the influence of the sheltered condition at Budaiya, where the dense vegetation cover tends to increase humidity.

The Sheikh Isa Air Base record has always greater diurnal range of mean relative humidity than at airport; up to about 20 % higher in July than the airport record (Meteorological Services, 1995). The monthly mean relative humidity at Sheikh Isa Air Base for the period 1991 – 1997 is shown in Table 2.13. It can be seen that relative humidity at this station exceeds that of the airport in winter and transitional periods by 2 to 5 %. During the summer months, however, Sheikh Isa monthly means are lower by 6 to 11 %. The annual average of about 62 % is nearly the same at both stations.

Winds

The annual average wind speed is about 9.3 knots. According to the airport authority, the highest wind gusts were recorded at 60 knots on February and April 1959. The predominant wind direction has a marked northwesterly component; and this is also the direction from which the strongest winds blow (Doornkamp *et al.*, 1980). The second most frequent winds have north and west directions that are together with the northwesterly winds represent about 60 % of the total winds. Collectively, these winds are locally termed as "Shamal". The less frequent winds in terms of their influence on Bahrain climate have a southeasterly direction and locally known as "Kous". The Kous winds represent about 18 % of the total winds, while the other less important winds make up the remaining 22 % (Isa, 1989). A rose diagram for the wind direction based on the analysis of the 1968 – 1997 records at Bahrain International Airport is shown in Figure 2.4.

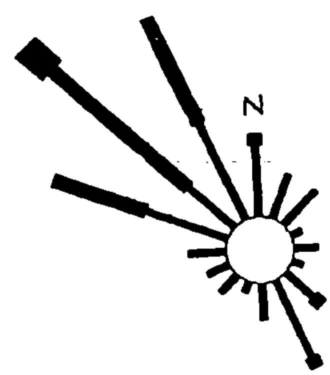
The "Shamal" winds have their direct influence not only on the climate conditions, where

Table 2.13 Monthly means relative humidity at Sheikh Isa Air Base and corresponding averages at Airport 1991 – 1997

Year	Monthly mean relative humidity (%)											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1991	---	---	---	---	---	---	---	---	---	---	64.7	74.4
1992	65.3	71.7	68.7	57.8	49.0	40.4	43.5	50.9	63.3	63.6	69.6	76.3
1993	75.1	73.2	59.6	63.2	49.0	43.2	49.1	54.5	63.9	65.7	70.6	76.6
1994	72.1	64.2	64.0	---	44.1	41.2	38.6	53.0	61.0	68.8	70.0	69.4
1995	76.1	74.0	69.8	59.8	50.8	46.2	50.0	63.2	61.4	68.0	72.1	84.9
1996	82.3	---	78.4	58.3	53.8	55.1	57.8	66.8	58.6	65.9	71.2	76.3
1997	73.6	64.6	75.5	62.1	48.2	51.5	44.2	47.0	60.3	69.8	79.6	77.3
Avers. monthly means	74.1	69.5	69.3	60.2	49.2	46.3	47.2	55.9	61.4	67.0	71.1	76.5
Corresponding averages at airport	71.1	68.1	66.4	58.7	50.8	50.7	52.6	59.7	61.7	64.4	67.3	72.6

SOURCE: Modified and adapted after Meteorological Services, 1995.
A dash indicates no records.

Figure 2.4 A rose diagram showing the wind directions at Bahrain International Airport



SOURCE: Meteorological Services

they produce relatively low humidity air masses, but also on the relief and landform characteristics of Bahrain Islands as will be explained in the section that follows. Their speeds vary from about 10 - 15 knots, averaging about 10.7 knots. Gusts and dust-raising winds of shamal type, however, can reach up to 30 knots; but such occurrence, according to Doornkamp *et al.* (1980), rarely sustained longer than three days. The Shamal winds occur predominantly during May and June, and normally produce high seas and persistent sandstorms (Isa, 1989). The winter shamal (December and January) is also common but less noticeable. The summer shamal, having passed over the Arabian landmass, is relatively cold and dry, and tends to modify the climate by lowering both temperatures and humidity levels.

The "Kous" winds blow over Oman and the Arabian Gulf area, and thus lead to an increase in temperature and humidity levels (NCMOFB, n.d.). These winds are more frequent in winter with an annual average speed of about 7.3 Knots. Their occurrence tends to produce fairly humid conditions, associated with common fogs, cloudiness and poor visibility.

The mean monthly wind speeds at Bahrain International Airport (measured at 10m) for the period 1977 – 1997 are listed in Table A-3 of Appendix A. The wind data at Budaiya, as shown in Table 2.14, once more closely reflect the protected nature of its location. The densely cultivated area, and the height of the measurement (only 2 m) resulted in monthly mean values well below the corresponding values at airport.

Means maximum wind speeds at Sheikh Isa Air Base, summarised in Table 2.15, are about

Table 2.14 Monthly means wind speeds at Budaiya and corresponding averages at airport 1974 - 1980

Month	Monthly mean wind speeds (Knots)							Average monthly means	Corresponding average at airport*
	1974	1975	1976	1977	1978	1979	1980		
January	---	2.6	2.5	2.9	2.3	1.6	1.9	2.3	11.4
February	---	2.4	2.8	2.1	2.2	1.6	1.8	2.2	9.9
March	---	3.1	2.3	3.0	3.3	2.0	1.8	2.6	10.9
April	---	1.7	2.0	2.8	3.6	2.0	2.3	2.4	11.0
May	---	2.5	2.4	1.8	1.9	1.5	2.2	2.1	9.5
June	2.5	3.3	3.0	1.9	3.1	2.7	2.0	2.6	12.0
July	2.3	2.1	2.5	2.3	1.5	1.9	1.4	2.0	9.9
August	2.7	2.1	1.9	1.3	2.2	1.7	1.6	1.9	9.6
September	1.9	1.6	2.4	1.2	1.8	0.8	1.5	1.6	7.3
October	1.2	2.5	1.3	1.8	1.1	1.4	1.4	1.5	8.5
November	1.9	2.3	1.9	2.6	2.6	0.9	1.4	1.9	9.9
December	2.6	2.6	1.6	2.0	1.3	1.8	1.8	2.0	10.6

SOURCE: Produced and modified after data obtained from Agricultural Affairs and Meteorological Services.
Notes: [1] *Based on 1977 – 1980 data.
[2] Adash indicates no records.

Table 2.15 Monthly means wind speeds at Sheikh Isa Air Base and corresponding averages at airport 1991 – 1997

Year	Monthly mean wind speeds (knots)											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1991	---	---	---	---	---	---	---	---	---	---	7.1	10.1
1992	9.9	9.5	8.8	8.2	9.4	10.9	10.6	8.2	7.5	6.9	8.2	9.6
1993	8.9	9.6	11.3	8.8	10.5	10.6	9.1	8.2	6.5	6.3	8.7	7.3
1994	7.7	9.9	8.5	8.6	9.8	11.0	11.5	8.6	7.6	6.6	8.7	10.0
1995	12.8	---	---	---	8.8	10.7	10.4	7.8	7.8	7.5	8.9	8.2
1996	7.6	9.5	8.9	9.9	8.2	9.8	7.9	6.9	8.4	7.7	---	---
1997	7.8	11.1	8.1	9.1	7.8	8.8	11.2	11.1	8.0	7.4	6.1	---
Average monthly means	9.1	9.9	9.1	8.9	9.1	10.3	10.1	8.5	7.6	7.1	8.0	9.0
Correspon. aver. at airport	9.2	10.5	9.4	8.7	8.7	9.8	9.4	7.9	7.4	7.3	8.9	9.2

SOURCE: Modified after the Meteorological Services, 1995.
A dash indicates no records.

1 to 2 knots greater than those at the airport from February through September; but are about the same at both stations during the rest of the year (Meteorological Services, 1995). As the table suggests, on average, the mean values at Sheikh Isa exceed the corresponding values at airport by about 0.4 knot, from April to September, with the extreme being in July at 0.7 knot. During the winter months, Sheikh Isa monthly means wind speeds are slightly less than those at the Airport.

The Awali record has been discontinued, but previous records analysed by GDC (1980a) indicated that the winds in Awali, particularly at shamal times, tend to be up to 60 % higher, gustier and have marked diurnal ranges than at airport. This reflects the high elevation (about 75 m above mean sea level), and the domination of desert condition at Awali. Unfortunately, these records were not made available for further analysis.

Sunshine

The mean monthly sunshine hours are reported to range from 11.3 hours per day in July to 7.1 hours per day in December. The long-term monthly means at Bahrain International Airport (Appendix A, Table A-4) produces an annual average of about 9.1 hours per day. This is literally the same as the annual average for the period 1974 – 1980, which was compared with the corresponding average at Budaiya. As illustrated in Table 2.16, the monthly means and the annual average at Budaiya are slightly lower than those at airport. The Budaiya annual average at 8.7 hours per day is about 4.6 % less than that at airport.

Atmospheric Pressure

Bahrain International Airport is the only station that has reliable instrument to record

Table 2.16 Monthly means sunshine hours at Budaiya and corresponding averages at airport 1974 – 1980

Months	Monthly mean sunshine (hours/day)							Average monthly means	Corresponding average at airport*
	1974	1975	1976	1977	1978	1979	1980		
January	4.9	7.2	6.1	7.5	8.4	6.4	7.0	6.8	7.0
February	7.4	7.1	6.6	8.5	7.9	8.1	6.5	7.4	7.7
March	5.4	8.0	6.2	8.5	8.3	7.5	7.7	7.4	7.3
April	9.4	8.2	7.3	7.7	6.2	9.6	8.7	8.2	8.6
May	10.0	9.9	9.9	10.5	10.0	10.2	9.1	9.9	10.3
June	12.0	11.4	11.8	10.5	16.0	9.4	10.8	10.8	11.3
July	12.0	11.6	10.1	10.0	9.8	7.7	10.2	10.2	10.8
August	11.4	10.9	10.5	10.0	9.1	5.1	10.2	9.6	10.8
September	10.2	10.0	10.2	9.5	9.8	8.8	9.2	9.7	10.3
October	9.4	9.5	8.7	8.0	8.8	8.3	8.4	8.7	9.3
November	8.6	9.0	8.5	9.0	6.8	7.9	7.6	8.2	8.6
December	6.3	6.4	7.4	7.0	7.2	7.2	7.1	6.9	6.9
Annual averages								8.7	9.1

SOURCE: Compiled and calculated from data made available by Agricultural Affairs and Meteorological Services.
* Based on the long term records 1968 – 1997.

atmospheric pressure. At this station, the annual average atmospheric pressure is about 1,009.8 hpa. This includes ranges from 997.6 hpa in July to 1,018.7 hpa in January (see Table 2.1). The maximum daily atmospheric pressure was recorded on 5 January 1992 at 1,031.6 hpa, while the daily minimum was recorded on 3 July 1974 at 991.1 hpa. A three-year record (1984 -1986) is maintained at Budaiya Station as shown in Table 2.17. The table reveals that although the daily mean at Budaiya is almost similar to the ones at airport, the calculated annual average at 1,015.4 hpa is slightly higher than the long-term average. It is to be noted, however, that the November 1986 value at Budaiya seems anomalous, because it considerably exceeds the highest value recorded at the airport. This value is probably responsible for the slight departure of the annual average at this station from the long-term annual average. Awali Authorities were used to keep limited records of atmospheric pressure but these records were not made available for processing.

Soil Temperature

Generally, very limited records are available on soil temperatures. Budaiya Station keeps two sets of limited data from 1984 to 1986, and from January 1997 to date. The first set contains a record of soil temperature measured at depths of 30 and 50 cm, from January 1984 to December 1986; and, at surface, 5, 10 and 20 cm, from November 1985 to December 1986. The second set measures the soil temperature at a depth of 50 cm. A one-year record (1978 – 1979) is available from Umm Nakhila Station, with measurements being taken twice daily at depths of 0, 5, 10 and 30 cm. The recently established climatological station at Howrat Aali Agricultural Project includes soil temperature measurement at a depth of 10 cm. The monthly mean soil temperatures at Budaiya from 1984 - 1986 and from 1997 - 1999 are illustrated in Table 2.18. The first set of records

Table 2.17 Mean daily atmospheric pressure at Budaiya Station 1984 – 1986 and corresponding averages at airport

Months	Mean daily atmospheric pressure (hpa)			Average monthly means	Corresponding monthly means at airport
	1984	1985	1986		
January	1021.6	1017.6	1020.3	1019.8	1018.7
February	1018.4	1016.6	1017.7	1017.6	1017.2
March	1013.1	1015.6	1015.3	1014.7	1014.0
April	1010.4	1010.8	1012.2	1011.1	1010.9
May	1006.0	1006.3	1008.3	1006.9	1006.9
June	999.9	1000.4	1009.6	1003.3	1000.9
July	998.1	999.7	1001.1	999.6	999.6
August	---	999.8	1004.7	1002.3	999.2
September	---	1007.0	1008.3	1007.7	1004.9
October	---	1013.0	1014.2	1013.6	1012.0
November	---	1016.0	1119.3	1067.7	1016.5
December	1019.9	1019.5	1022.4	1020.6	1018.5
Annual averages				1015.4	1009.9

SOURCE: Prepared and calculated based on data made available from the climatological records Agricultural Affaires.
A dash indicates no records.

Table 2.18 Monthly means soil temperatures at Budaiya Station 1984 - 1986 and 1997 - 1999

Months	Mean soil temperatures (° C)			Monthly average	Mean soil temperatures (° C)			Monthly average
	1984	1985	1986		1997	1998	1999	
January	11.0	18.6	18.2	15.9	20.9	18.5	21.3	20.2
February	12.0	18.4	17.6	16.0	21.8	20.0	21.5	21.1
March	16.0	20.2	19.8	18.7	22.4	22.5	23.0	22.6
April	20.0	25.3	23.2	22.8	25.4	26.0	26.9	26.1
May	24.0	29.2	27.0	26.7	29.6	29.7	29.5	29.6
June	27.0	30.2	30.0	29.1	32.5	33.0	32.8	32.8
July	28.0	31.4	33.0	30.8	33.6	34.0	33.9	33.8
August	--	32.7	32.0	32.4	34.1	35.4	34.5	34.7
September	33.4	31.7	31.5	32.2	33.3	34.4	34.1	33.9
October	30.5	28.9	31.4	30.3	31.7	31.7	31.2	31.5
November	--	25.9	24.8	25.4	25.9	27.5	27.7	27.0
December	20.6	20.7	20.5	20.6	21.8	24.1	23.1	23.0

SOURCE: Modified after the Agricultural Affairs
Note: 1984 – 1986 records are taken at 30cm, while 1997 – 1999 records at 50cm.

represents 30 cm depth, and the second was taken at 50 cm. As shown in the table, soil temperature ranges from 18.6 °C in January to 32.7 °C in August for the first set of data, and from 20.2 °C in January to 34.7 °C in August for the second set of data.

Seawater Temperature

The temperature of the shallow seawater around Bahrain is very high, and is confined to a range between 17 °C in February to 33 °C in August. On the basis of the limited data available, it seems plausible to assume that the monthly mean seawater temperatures are commonly less than the monthly mean air temperatures by about 2 °C.

2.3 Topography and Physiography

Generally, Bahrain is a flat area in which altitude ranges from slightly above mean sea level in the coastal areas to about 122.4 m in the central part of the main island; with the average altitude being 20 m above mean sea level. The geomorphology and landforms development in the study area are closely controlled by the geologic outcrops, lithology and structure (ALECSO, 1975; Brunsden *et al.*, 1976a; Doornkamp *et al.*, 1980).

Much of the study area is composed of (1) shallow marine carbonate rocks of the Eocene age; within which internal catchments, extensive playa basins, numerous pluvial and aeolian geomorphic features, including network of ephemeral streams have been identified, and (2) a widespread coastal plain of Pleistocene-Holocene age, characterised by plentiful dune systems, beach ridges and sabkha lowlands (ALECSO, 1975; Brunsden *et al.*, 1976a; Doornkamp *et al.*, 1980).

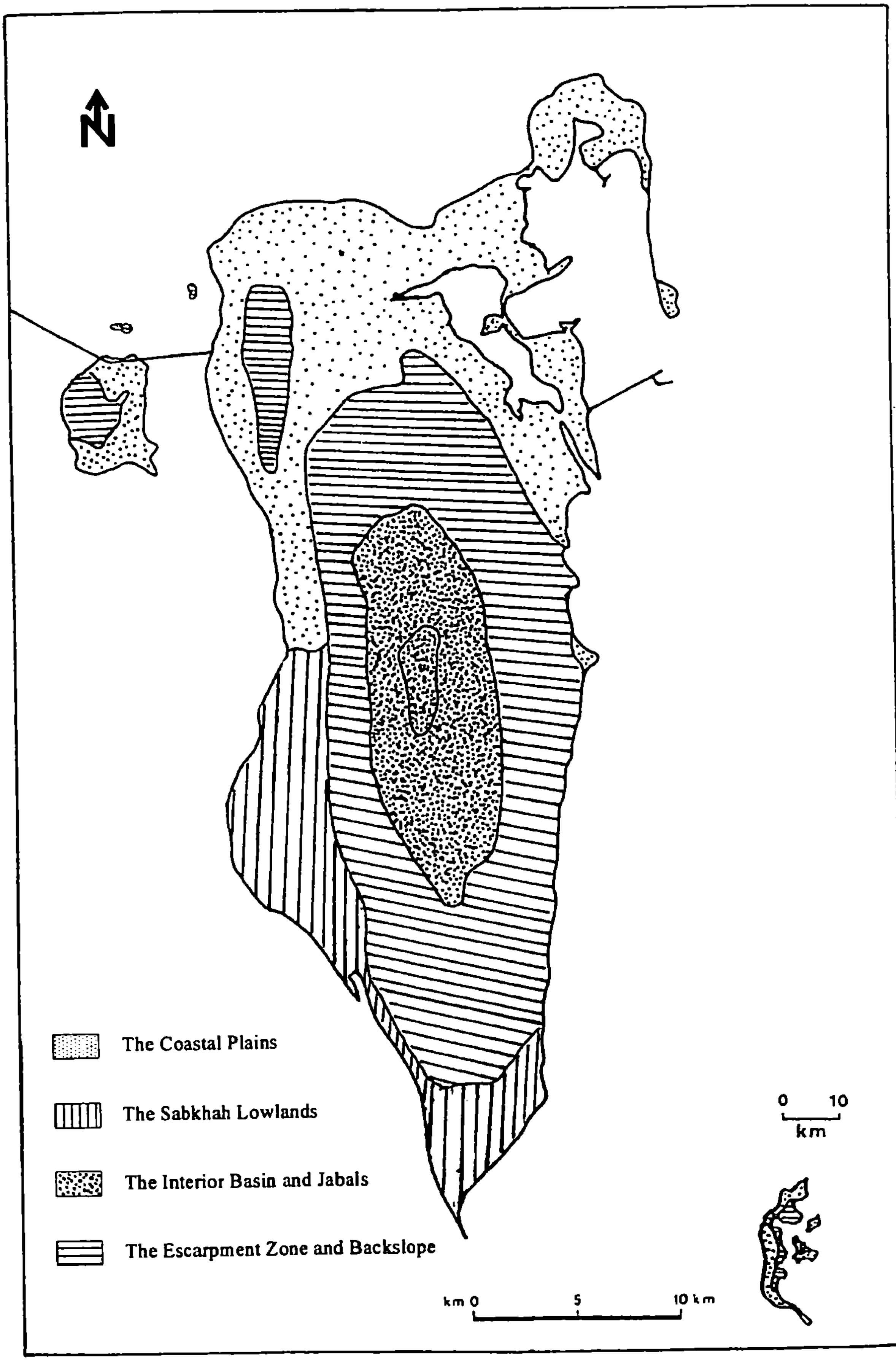
Physiographically, the study area can be divided, as shown in Figure 2.5, into four physiographic regions: the coastal plains, the multiple escarpment zones and backslopes, the interior basin and jabals, and the sabkha lowlands. While I have slightly modified their classification of the physiographic regions, and based much of my discussion on the interpretation of their valuable geomorphic maps supported by some field observations, the pioneer work on the geomorphology and physiography of Bahrain carried out by Doornkamp *et al.* (1980) was the most important source for the preceding discussion. The detailed description of the geomorphic features evolved from the interpretation of the geomorphology and superficial materials map sheets produced by Brunsden *et al.*, (1976a) at scales of 1: 10, 000 for the Bahrain Main Islands group, and 1: 30, 000 for Huwar Islands group. It is to be mentioned here that for the places names that will appear throughout this section, the reader should consult the study area location map in Figure 2.1, so that localities discussed can be followed in their geographic positions. This map may also be useful for the discussion throughout the geology section.

The Coastal Plains

This region covers the northern coast of Bahrain main island and extends along its western coast from Budaiya down to the northern edge of Zallaq. It also extends along the eastern coast from Manama to Maameer, and covers extensive parts of the offshore islands, including Muharraq, Sitra, Nabih Salih and Umm Nassan. This region also occupies large parts of the Huwar Islands.

The northern coastal plain of Bahrain Island is a broad, poorly drained region, rising from about 10 m behind the backslope to slightly above sea level near the coastlines, but most of

Figure 2.5 The physiographic regions of Bahrain



its surface is generally less than 6 m above mean sea level. It is composed of superficial materials of unconsolidated sand, silt, and quartz sand of Quaternary age which normally form a thin sheet overlying bedrock of beach rock materials or limestone of Miocene or middle Eocene age (Bridges and Burnham, 1980). In some places, such as Al-Hajar, Moqsha, Barbar, Shakhoora and more distinguishably in Isa town, the plain is broken by irregular bedrock exposures in the form of small isolated inliers of possibly Miocene or middle Eocene age. Although, most of the northern coastal plain has been extensively modified and worked out by man for his agricultural and urban activities, prominent geomorphic features of low-lying, loosely cemented sand dunes can be easily discerned at surface (Brunsden *et al.*, 1976a).

Inland, near Al-Murkh, Bani Jamra, Saar and Muqabah villages, the dunes gradually rise in elevation to form an extensive dune field of nebkha type; but these seldom exceed 15 m. The dunes, which are largely composed of gypsiferous quartz-sand, are believed to be an accretion ridge representing an ancient shoreline (Doornkamp *et al.*, 1980). Further inland near Salmabad and Aali villages, the dunes are considerably reduced in elevation and intermingled with various coastal plain deposits and sabkha surfaces. To the east of these areas, near Tubli village, the dune fields give way to a narrow shallow embayment known as Khor Maqtaa Tubli or Tubli Bay. The bay area used to be a rich and varied marine environment, but recently has suffered environmental deterioration because of coastal reclamation, uncontrolled urban development, and discharge of wastewater from the nearby treatment plant.

The western coastal plain is an extensive sand plain, rarely exceeding 4 m in altitude. It slopes away from the bedrock towards the coastlines. The shorelines are formed mainly of low-lying beach ridges composed chiefly of poorly graded quartz-sand and shelly gravel. Inland, the surface is slightly elevated, and is covered by relatively low elevation nebkha dunes. The area extending from Dumistan village to Az-Zallaq in the south is extensively modified by cultivation. The surface at those localities is mainly covered by gypsiferous sand and gravels, with scattered low-lying salt-encrusted nebkha dunes. In places near Dumistan and Karzakan villages, for example, rock outcrops (stone pavements) of mainly upper Dammam limestone occasionally interrupt this rather monotonous coastal plain. To the south and east of Dar Kulaib village near the edge of the backslope, these give way to prominent exposures of Middle Eocene rock. Notably, the western coastal plain as reported by Doornkamp, *et al.* (1980) has been dissected near the Hamala Camp by bedrock exposure of Middle Eocene age, which forms a north-south trending anticline, marked at its eastern edge by a large depression known as the Lawzi Lake.

Elsewhere, in Muharraq Island, Doornkamp *et al.* (1980), recognised that the coastal plain attains elevations of between 2.1 and 2.4 m, and consists of slightly elevated areas formed of Quaternary limestone or fixed vegetated dunes, linked by a slightly elevated beach-ridge complex. The coastlines in this island have generally rocky appearance formed of raised platforms and beach-ridge complexes, with elevations commonly not more than 3 m. These are made up of poorly-graded, partially cemented, shell-rich limestone and calcareous quartz-sand, with common hollow structure, algal quartzose limestone.

Brunsden *et al.* (1976a) noted that the platforms slope gently inland and follow the coastlines from Arad to Hidd and Muharraq itself. More perceptible platforms, though slightly lower in elevation, form the coastline of Al-Halat (a local terminology for small island). Land reclamation and urban development have obscured most of the original geomorphic relief of these platforms, particularly near the Hidd Peninsula, and Arad and Qalali villages. The northern coastal plain of Muharraq is mainly occupied by low level sand dunes standing at altitudes between 1 – 3 m, and predominantly composed of poorly graded and loosely cemented quartz-sand veneered, in places, with gypsiferous layers. Brunsden *et al.* (1976a) demonstrate that along the coastlines, the dunes rise gradually to produce elevated beaches, beach platforms and tongues, suggesting erosion by wave action. They also noticed that inland, in Qalali and near the airport, the surface is highly encrusted with gypsum, and is generally featureless with few preserved original geomorphic features. The rest of the northeastern coastal plain has markedly flat, sabkha-like surface, which grades into sheltered intertidal zones at Dowhat Arad, Dowhat Az-Zimah, and Muharraq bay. Increasing reclamation and urban settlement, particularly in Arad and Qalali villages have destroyed most of the sabkha characteristics.

The eastern coastal plain is mainly characterised by sabkha flat deposits and rock outcrops of presumably Quaternary age that vary in elevation from almost sea level to 6 m above mean sea level. Again, prolonged cultivation and settlement have largely obscured the original morphology and superficial primary depositional features (Doornkamp *et al.*, 1980). The northern coast of Sitra Island is formed by elevated beach-ridges, while its southern coast near Halat Umm Al- Baidh is normally flat lying, dominated by sabkha-forming deposits. The Nabih Salih Island shorelines are characterised by a slightly elevated beach-ridge complex. Away from these shorelines, the inland geomorphic features of this island have been partly, if not entirely, masked by extensive cultivation and increasing urban development. Further south in Al-Akur, Nuwaidrat, and Maameer villages, much of the surface is relatively featureless, and is dominated by low-lying highly encrusted sabkha-like materials, although dune fields of nebkha type are found in the eastern parts of Nuwaidrat. In the vicinity of Sanad, these dunes appear to have been rather dissected by well-exposed rock outcrops. Evidently, most of these areas are now increasingly being covered by urban and industrial development.

Doornkamp *et al.* (1980) postulated that the landforms in Umm Nassan Island are either formed of Miocene bedrock or rock platforms, thinly veneered by marine shell gravels, with low-lying, nebkha dunes occupying most of its inland parts. The materials that compose the dunes are mainly loose, homogenous, poorly-graded, often gypsum-encrusted calcareous quartz sands. The coastline morphology is dominated by low relief raised beaches and marine platforms, with the exception of the southern coastline in which sandy beaches appear to be dominant.

In Huwar Islands the landforms do not appear to be significantly different from those on the Bahrain main Island (Doornkamp *et al.*, 1980). Large areas of these islands are formed of scattered nebkha dunes, exposed bedrock of principally undifferentiated carbonate rocks, partly covered with thin gravel. One of the most prominent features in these islands, however, is the continuous beach ridge complex, which extends along the western coast of the Huwar main Island and ends at its southern point with a narrow and elongated sand spit. This ridge reaches a maximum width of over 300 m but seldom exceeds 1 m in thickness. It is chiefly composed of rather homogenous shelly and oolitic sand and marine shell materials (Doornkamp *et al.*, 1980). The eastern coasts of Huwar Island are dominated by coast-facing scarps sloping steeply towards the sea, with elevations of between 2 – 5 m above mean sea level. Its surface attains heights of between 2 m in its northern and southern parts, and about 6 m in the central parts. The other islands have generally low relief; with elevation rarely exceeds 1.8 m.

The Multiple Escarpment Zone and Backslope

The multiple escarpment zone is a continuous inland-facing scarps surrounding an interior basin. The scarps vary in elevation from 40 - 60 m above mean sea level in the south and north to generally less than 30 m in the western and eastern parts. Width is also variable, depending on the magnitude of erosion but normally ranges from 1 – 3 km. The zone is considerably thinner in the middle parts, where the interior basin widens towards the coasts. The escarpments are composed essentially of carbonate-shale deposits of the Eocene age. Soft shale-claystone sediments are normally topped by resistant limestone - dolostone (dolomite limestone) rocks, providing appropriate cliff-forming conditions. Therefore, the escarpments show considerable variation in form, from single bold escarpment to multiple steps and benches forming escarpments (Doornkamp *et al.*, 1980). Apart from minor gaps, the most important of which is the one near Az-Zallaq in the western side, the escarpment zone almost completely surrounds the interior basin.

In their study of 1976, Brunsden *et al* showed that the escarpment zone can be divided into two sub-zones, each of which extends about 28 km, and they meet at the north and south to surround the interior basin. They found that the eastern escarpment is lower in elevation, attaining a maximum altitude of about 45 m near Ras Abu-Jarjur. The elevations decline gradually to the south and north of this point to between 15 – 30 m.

The western escarpment is normally higher in elevation by an average of 10 m, and reaches its maximum altitude of about 60 m north of Ar- Rumaithah.

The escarpment surface is characterised by numerous, normally shallow and steep drainage systems and ephemeral streams, which considerably vary in patterns, depths and lengths. ALECSO (1975) identified two major drainage systems in the western scarp; namely, (i) the Az-Zallaq drainage system, which runs for about 6 km, from the interior basin to the north of Az- Zallaq village; and (ii) the Buri drainage system which starts from the interior basin, and runs for 7 km towards the eastern edge of Buri village. The main drainage system at the eastern scarp is the wadi system south of Refinery that also originated from the interior basin and cuts through the escarpment north east of Awali to drain in an area located south of the refinery.

The most prominent geomorphic feature at the surface of the escarpment zone is the so-called north west playa. This is an extensive depression completely bounded by the scarps zone. The surface of this playa has a lowest point of 19 m, which is between 8 and 22 m below the crest of the surrounding scarp (Doornkamp *et al.*, 1980). This surface is composed predominantly of moderately to well-sorted sand and gravels, with some isolated stone pavements and bedrock exposures. In few places, these materials are often obscured by widely scattered small shrubs, nebkha dunes and vegetation of halophytic type. Away near the foot of the scarps, such materials are separated by rather poorly-developed alluvial fans.

The **backslope** is an inclined surface sloping away from the escarpment zone towards the coastal plains (Doornkamp *et al.*, 1980). The term "Backslope" is first suggested by Brunsden *et al.* (1976a), to show that the topographic surface of the backslope strata cuts across the bedding, so that higher and younger beds are encountered as the coast is approached. This implies, as assumed by the same researchers, that the feature is erosional in nature and not a true dipslope. The backslope is broad in the north and south, but extremely narrow in the west and east, generally reflecting the asymmetrical nature of the Bahrain Dome (Doornkamp *et al.*, 1980). In the northwest and north of the backslope, the surface is dominated by bedrock exposures that usually form secondary scarps. Farther north near Aali, a depression of an irregular surface is developed within the backslope surface. This depression contains several drainage systems that cut across recent sediments of gravels and coarse sand, and some older bedrock exposures. Most of these drainage systems are now being interrupted by sediment-filled depressions.

The Interior Basin and Jabals

The interior basin is an elongated depression surrounded by the escarpment zone, and formed by the erosion of the crest of Bahrain Dome. It has an erosional inlier surface made up of the lower Eocene rocks. The basin surface is asymmetrical, and varies in width from 2.5 km in the west to a maximum of 8 km in the south; and in elevation from over 70 m in the southeast of Awali to a minimum of 5 m in the southeastern part (Doornkamp *et al.*, 1980). It is characterised by the presence of numerous geomorphic features, such as marginal depressions, playa basins, and bedrock exposures of mainly lower Eocene age, forming isolated hills and plateaus. There are also some drainage streams (mainly of dentritic patterns), patches of remnant nebkha dunes, and isolated small dayas.

The enclosed depression areas are often filled with fine to medium grained, gypsum-rich silts and sands. The playa basins' surfaces are primarily made up of low-lying alluvial fan deposits of gypsiferous sands and gravels, near the foot of the scarps, grading to well-sorted, silts and clays, with common evaporites (mainly anhydrite) towards the centres. The southern playa represents the lowest area in the interior basin with land surface elevation ranges from 5 – 8 m. It occupies an area of about 65 km^2, and consists of two major playa basins; namely, Al-Ghaynah and Ash Shabak (Doornkamp *et al.*, 1980). The land surface of the former basin is largely composed of rock exposure, with gypseous sand and gypsum- encrusted gravels near the slope sides. In Ash Shabak, the surface is predominantly covered with gypsum-encrusted sands and gravels.

Large areas of the basin surface, particularly those around the foot of the jabals are covered by bedrock surface modified by wind action (wind-faceted bedrock of Brunsden *et al.*, 1976a). Karstification is confined to small areas in the southern and northern parts of the basin, and on the eastern flank near Ras Abu-Jarjur. The karst features, at those locations, are represented by isolated shallow dayas, small caverns, and near the surface solution channels. Elsewhere, especially along the lower Dammam cliffs at Al-Buhair depression and in the vicinity of Ras Abu-Jarjur at the eastern escarpment, surface joints and fractures presumably of karstic nature are found.

Numerous drainage streams of various patterns, lengths and depths are found throughout the interior basin area. Most of these streams are endoreic in nature (i.e. they drain within the interior basin and away to its marginal sedimentary depressions). It is believed (Doornkamp *et al.* 1980), however, that these streams have clearly found their way in the past through the main escarpment. This has probably occurred via three major outlet channels, the most important among which is Az-Zallaq outlet (gap) at the western escarpment zone. This gap was possibly responsible for draining off the eroded sediments away from the basin area; thus largely contributing in the formation of the interior basin. At present, this gap together with Al-Wasmiyyah outlet to the south act as pathways for transporting the sediment materials during intense rainstorms. Low-lying dunes of both normal and nebkhah types are scattered throughout the interior basin. Typically, they are largely made up of variably graded aeolian deposits, with the nebkhah dunes being covered with halophytic plants.

The **jabals** are isolated remnant hills and plateaus formed by outcrops of resistant rocks standing distinctly above the surrounding ground. The average elevation of these jabals is approximately 60 m, but Jabal Ad-Dukhan, the highest point near the centre of the interior basin, stands at about 122.4 m above mean sea level. This jabal is one of the most conspicuous topographic features in Bahrain, and is basically a flat-topped surface plateau, and lies at various heights with the maximum being in the northern side, decreasing steadily to the minimum in the southern side. At this lowest point, the jabal declines in altitude to descend within the interior basin bedrock surface. Standing to the east of Jabal Ad-Dukhan are two steep-sided hills reaching an elevation of about 70 m, known as Al-Rumanateen plateaus. These are separated from the main Jabal by a relatively raised surface made up of wind-faceted bedrock.

This physiographic region also contains several hills of mesa and cuesta types, varying in altitude from 30 – 60 m. The most prominent examples of which are Ar-Rumaithah, Safrah, refinery and Al-Buhair cuestas, and the gypsum mesa south of Awali. In most cases, resistant, cliff forming, often duricrusted dolostones form the summits of these features; below which are rather soft and commonly weathered dolarenite/dolosiltite, or shale beds. This has created favourable conditions for the differential weathering to operate; thus producing small caverns and over-hanged walls. For instance, such phenomena is well developed in the cuestas of Al- Buhair depression, where the underlying weak rocks of the Middle Eocene have been extensively eroded by salt weathering and solution processes to produce numerous caverns, topped by over-hanged resistant cap rock.

The Sabkha Lowlands

The major sabkhas in the study area are commonly low-lying marginal coastal flats. Minor playa basins and sabkha-like deposits are found inland from the coast (continental sabkhas), within the topographic depressions (the previously described Ash Shabak and Al-Ghaynah Playas). The intertidal - subtidal zones in and around the coastal plain, including Khowr (an Arabic term for the shallow embayment) Tubli, Arad and Az-Zimmah mud flats, Halat Umm Al-Baidh, and the coastal sabkha near Ras Hayyan, are considered here as part of the extensive coastal plain, and are briefly described earlier.

Therefore, the following discussion only deals with the major coastal tidal-flats, namely; the Southwest Sabkha, and the South Sabkha. These occupy a narrow belt along the southwest and southern coasts of the Bahrain main island (see Figure 2.5). The detailed morphology and sedimentology of these sabkhas are beyond the scope of this research, but can be found elsewhere in the literature (e.g. Brunsden *et al.*, 1976a; Doornkamp *et al.*, 1980).

The Southwest Sabkha extends from south of Az-Zallaq up to the southern end of Bahrain main island. It occupies an area of about 60 km^2, with elevation ranging from 6 m in the north near Al-Murkh to at sea level in Al-Mummattalah (Doornkamp *et al.*, 1980). The seaward margin of this sabkha is dominated by a beach ridge complex forming longitudinal accretion zone of shell-gravel platforms. This beach complex is reported to vary in elevation from about 3m near Al-Jazair to almost sea level in the south where it somewhat loses its geomorphic definition (Brunsden *et al.*, 1976a). Along the western coast the beach complex is separated from the shoreline by a narrow sandy-gravel beach zone. The area between the beach complex and the backslope margins is narrower in the north near Al-Murkh and Wadi Ali, but markedly widens towards the south near Al-Mummattalah where it forms an extensive salt pan of typical salt-encrusted sabkha surface (Doornkamp *et al.*, 1980).

This area, which is known locally as Mamlahat (An Arabic term for sabkha, where salt is, or at one time was mined according to Powers *et al.* (1966)) Al-Mummattalah, represents the biggest sabkha surface in Bahrain. This surface is largely composed of variably graded gypsiferous and quartzose sand, veneered with a blistered gypsum crust, resulting from evaporation of shallow groundwater. Apart from some nebkha dunes in the north, the sabkha surface is characterised by absence of vegetation (Doornkamp *et al.*, 1980). It forms low-lying supratidal/intertidal flats, which are often subjected to periodic flooding by rainwater or marine water during high tides. This is commonly followed, in dry seasons, by continuous deflation of the deposited materials and evaporation from the capillary zone, which contributes to salt accumulation.

The sabkha grades landward into a broad area to occupy various geomorphic features, including a remnant beach ridge, isolated nebkha dunes, and minor stone pavements. Outward from the shoreline, the sabkha is bounded by a slightly elevated surface of rock outcrops. Here the sabkha brine water appears to recharge the exposed aquifer, causing its salinity to increase to up to 15,000 mg l^{-1}. This has its important implications on the groundwater quality distribution as will be discussed in the next chapter.

The South Sabkha occupies an area of about 30 km^2. It continues from the southern backslope to the farthest point of Bahrain main island. This point is a longitudinal sandspit known as Ras Al- Bar. Unlike the Southwest Sabkha, the South Sabkha broadens progressively northward to a maximum width of 6 km close to its junction with the solid rocks of the southern backslope, forming a triangular coastal plain (Doornkamp *et al.*, 1980). In the southern end near the sandspit, the sabkha narrows considerably to about 250 m. The low-lying surface of this sabkha permits periodic tidal invasions and inundation by rainstorms.

In terms of sediment framework, there is a close similarity between the South Sabkha and the Southwest Sabkha. Seaward, the remnant beach ridge continues along the western coast, and is dominantly composed of shelly gravel, veneered with a gypsum crust, with nebkha dunes covering only minor portions of the surface. Inland from the coastline, the elevation generally increases towards the backslope area, where the typical sabkha sediments give way to solid rocks of bioclastic dolomitic limestone (Doornkamp *et al.*, 1980). Over most of the eastern shoreline, the surface widens to form a broader sand plain, made up of loose and homogenous calcareous sand, often encrusted with gypsum.

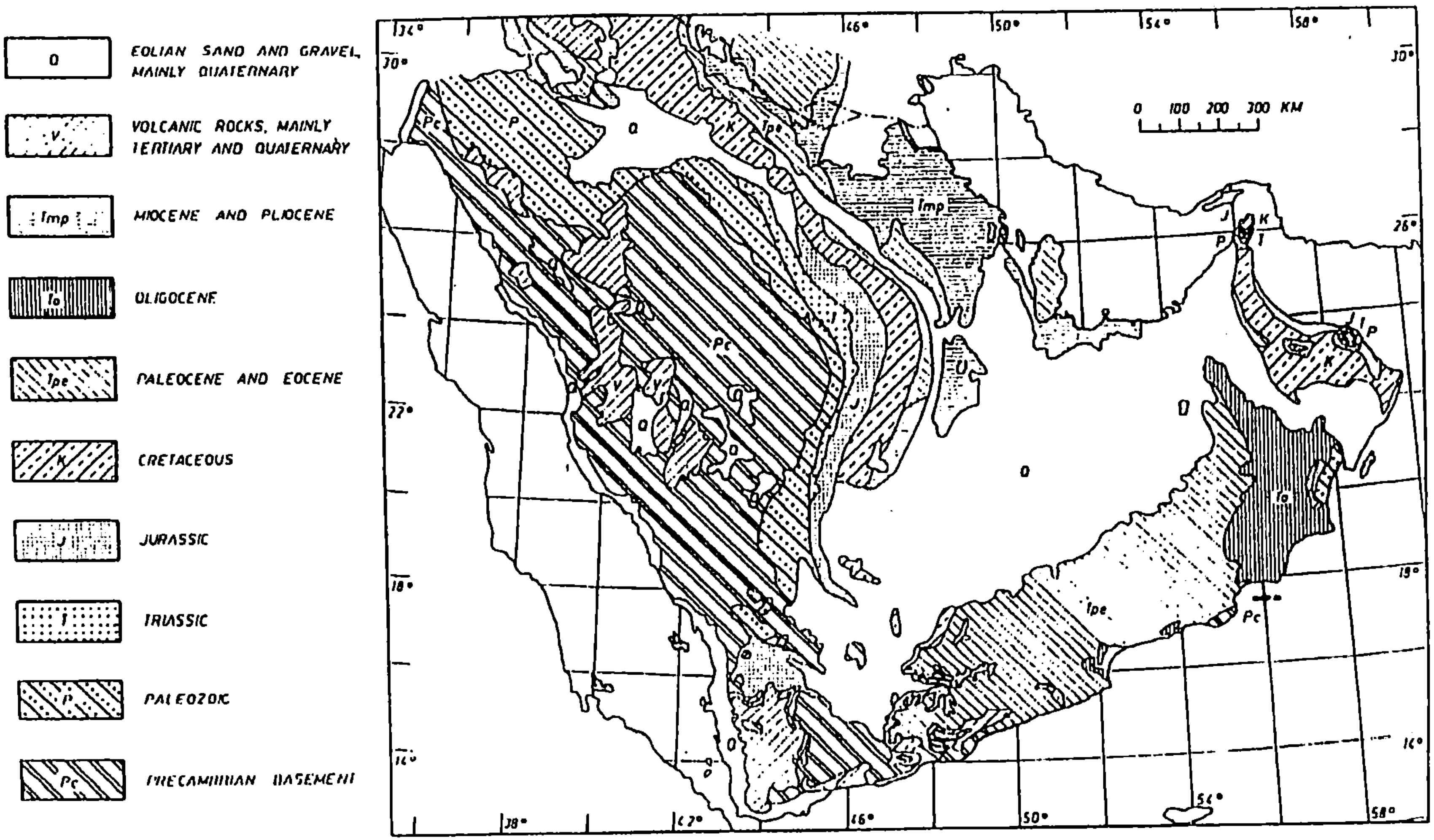
2.4 Geology

2.4.1 Regional Setting

The Arabian Peninsula is a huge crustal plate, deformed and metamorphosed during the Early Precambrian and extensively eroded and peneplained during the Late Precambrian (Chapman, 1978). In the period from the Cambrian to the Early Cenozioc, the area witnessed a continuous slow subsidence and transgression of broad epicontinental seas, which spread widely to the east of the Arabian Peninsula, resulting in the deposition of relatively thin successions of almost flat-lying Paleozoic, Mesozioc, and Early Cenozioc strata (Powers *et al.*,1966). These transgression episodes are followed from time to time by regression cycles that produced several unconformities. Figure 2.6 is the generalised geological map of the Arabian Peninsula.

The northeastern and eastern sides of the plate had experienced several orogenic movements that continued from the Late Cretaceous time up to the Late Tertiary (Mio - Pliocene). In the Late Tertiary time, these eastward thrust movements have resulted in upfolding of deep-seated sedimentary basins in a form of great mountain ranges – the Zagros - Taurus Mountains in Iran and Turkey, and the Oman Mountains, and in major block fault movement - the Red Sea Graben (Powers *et al.*, 1966; Chapman, 1978). These movements are also associated with extensive volcanism, particularly in the western parts of Saudi Arabia. The Red Sea Graben movement, in particular, has links with the great Alpine – Himalayan Orogeny (Powers *et al.*, 1966; Chapman, 1978; Kent, 1978) and led

Figure 2.6 Generalised regional geological map of the Arabian Peninsula (after Chapman, 1978)

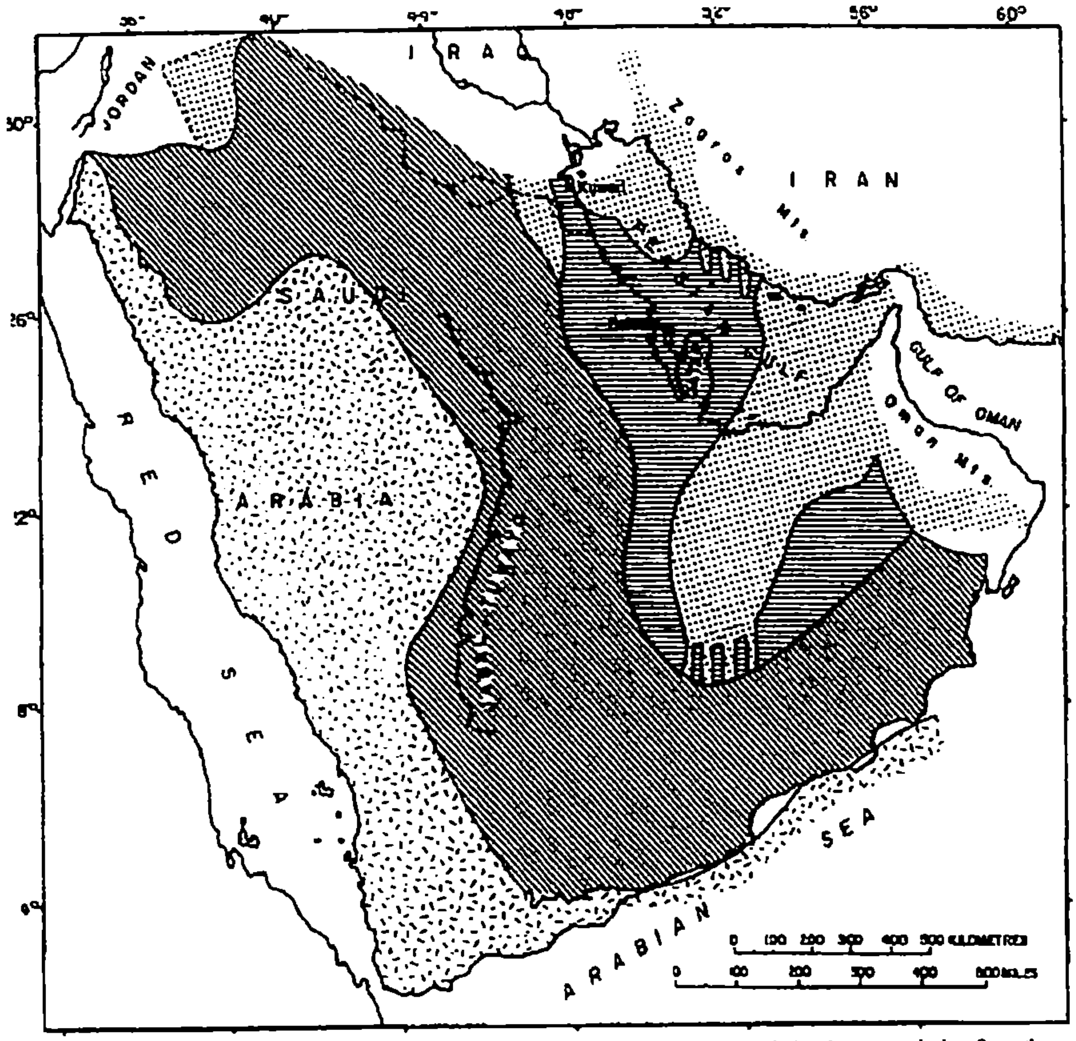


Reproduced by kind written permission from Springler-Verlag Wein to the continental separation of the Arabian Plate from the African Plate at/along the western side, most probably during the Late Miocene – Early Pliocene time. At that time, minor broad folding was in evidence, but the region has been relatively structurally stable since the Pliocene (Larsen, 1983).

Within this broad tectonic framework, two major structural provinces can be recognised. One is comparatively stable whose rigidity is controlled by the Precambrian basement, and the other is the great mobile belt (Powers *et al.*, 1966). The former is made up of the basement complex, and the relatively thin sedimentary sequences of the Paleozoic, Mesozoic and Early Cenozoic periods (see Figure 2.6). The mobile belt borders the stable region from the northeast and east, and includes the Zagros-Taurus Mountain ranges and the Oman Mountains. The structural provinces in the Arabian Peninsula and its adjacent areas are shown in Figure 2.7.

The stable region, as illustrated in Figure 2.7, is subdivided into two structural sub-provinces: the Arabian Shield and the Arabian Shelf. Power *et al.* (1966) described the Arabian Shield as a rigid, peneplained, and slightly-arched surface composed largely of a Precambrian basement complex of igneous and metamorphic rocks, occasionally covered by Paleozoic continental deposits and Tertiary lava floods. The Arabian Shelf consists of relatively thin sedimentary sequence of continental and shallow marine deposits, resting unconformably on the basement complex (Chapman, 1973). The sedimentary rocks that form the shelf vary in age from the Late Palaeozoic to the Pliocene (Figure 2.6). They dip gently eastward away from the shield towards the Arabian Gulf and Rub' al-Khali basins.

Figure 2.7 Structural provinces of the Arabian Peninsula (after Kent, 1978)



Reproduced with kind written permission from the Geological Society of London

LEGEND

STABLE REGION

ARABIAN SHIELD

ARABIAN SHELF
Interior Homocline

Interior Platform

Basins

The Arabian shelf is further subdivided into three structural sub-regions. The Interior Homocline, the Interior Platform, and the Basins (see Figure 2.7). The Homocline is a great, commonly undisturbed sedimentary belt bordering the shield from the east, with an average width of about 400 km (ARAMCO, 1975). The Interior Platform is a flat structural feature separated from the homocline by an abrupt-break in slope (Chapman, 1978). It is largely made up of shallow to restricted marine deposits of Cretaceous and Tertiary age, dominantly limestone and shale, with subsidiary continental sandstone (Figure 2.6). The width of the platform ranges from about 100 km along the southern and western sides of the Rub'al Khali Basin to 400 km or more across the Qatar Peninsula (Powers *et al.*, 1966).

As previously indicated, both the Homocline and the Platform have been tectonically stable since the Pliocene time. Murris (1980) postulated that, apart from the orogenic activities during the Cretaceous and Tertiary, the depositional history of the Arabian shelf was generally characterised by stable conditions. The stable and flat-lying surface of the platform is, however, interrupted by several north-south trending anticlinal trends, which rise above the general level of the platform, and include the major oil field in Arabia (Ayers *et al.*, 1982). Bahrain lies within the northeastern edge of the Interior Platform, and the Bahrain Dome - the dominant structural feature in the country - is one of these anticlinal structures.

The Basins are deep synclinal depressions filled with relatively thick Miocene-Pliocene and Quaternary sediments. They lie on the edges of the platform, with only one major basin (the As-Sirhan-Turayf basin) lies on the northwestern margin of the homocline adjacent to the Jordan borders. The other major basins are: the Ar Rub Al Khali basin, the northern Arabian Gulf basin, and Ad Dibdibah basin (Figure 2.7).

2.4.2 Structural Framework

Bahrain is a surface expression of an approximately 30 × 10 km, elongated, slightly asymmetrical north-south trending anticline known as the Bahrain Dome. This dome is a periclinal structure developed in the Tertiary carbonate sediments of Lower – Middle Eocene (Ypresian – Lutetian). The dominant lithologies are limestone and chalky limestone, extensively modified by dolomitization. Off-dome synclinal areas are characteristically thin beds of dolomitic limestones, with subsidiary shales and marls.

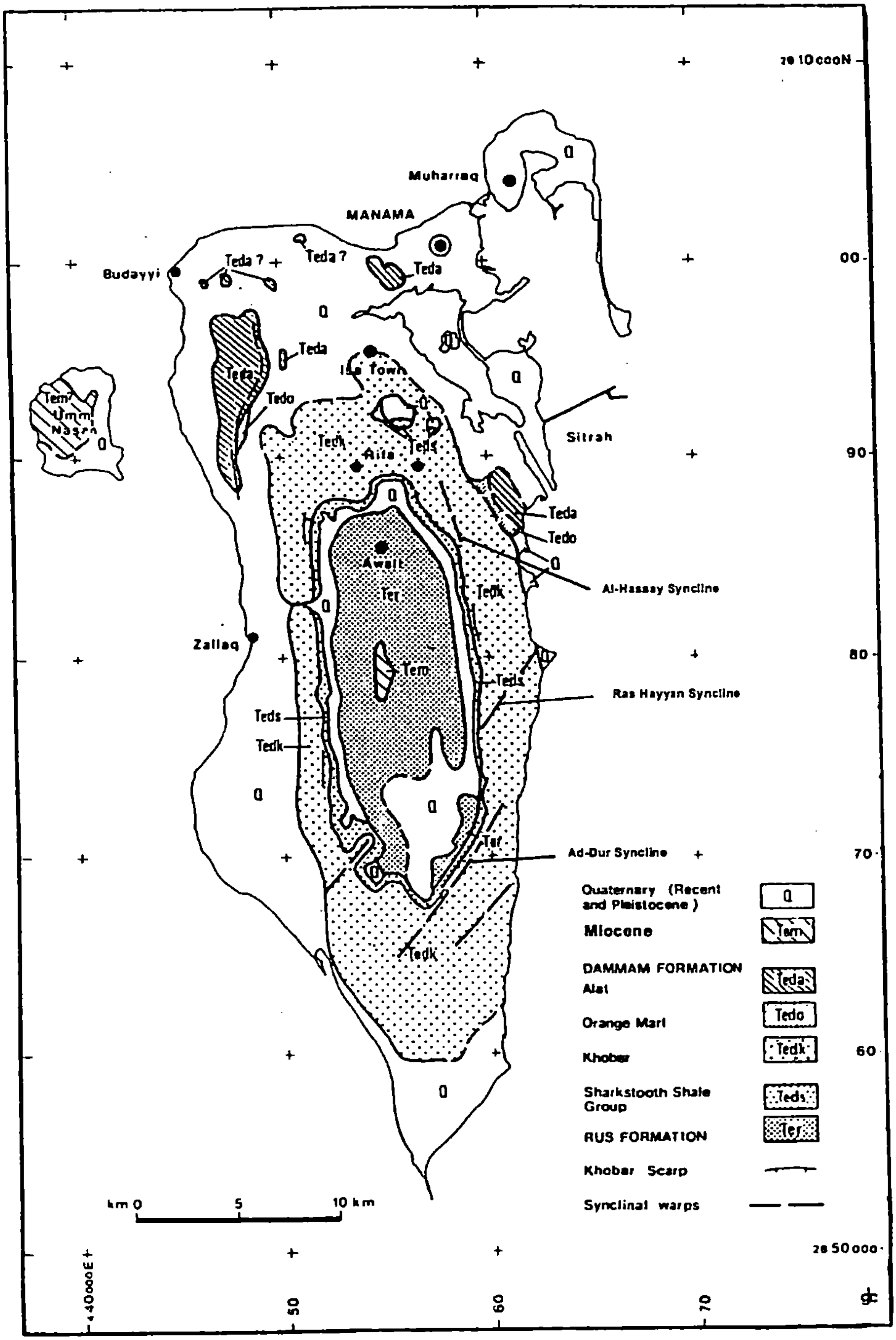
Depositional thinning occurs over the crest of the dome, whilst thickening takes place in off-dome synclinal areas (GDC, 1980b), indicating synsedimentary structural growth (i.e. the dome structure was slowly developing during the deposition of the Eocene strata). The anticline dips asymmetrically to the east and west at generally less than 5 degrees. The steeper west flank has dips of 4 degrees and the gentler eastern flank dips 2 degrees (Samahiji and Chaube, 1987). According to Steineke (1942), the northern plunge of the dome has been eroded less than the southern plunge - the later has been deeply eroded to expose the Lower Dammam rocks, which, in turns, is overlapped by younger Miocene and Quaternary deposits over a relatively large area.

Local and regional uplift near the close of the Middle Miocene initiated a period of erosion, and no Upper Eocene and Oligocene sediments have been recognised in Bahrain (Willis, 1967). Further uplift during the Late Miocene - Early Pliocene has resulted in the erosion of the Middle Eocene and most of the Miocene rocks; thus exposing the Lower Eocene beds. This has led to the formation of an erosional inlier basin – the Interior Basin. Bahrain owes its present striking shape largely to these major uplift and erosional episodes.

The erosional edges of the Bahrain Dome are represented by inward facing escarpments of the Middle Eocene (Dammam Formation) rocks that surround the eroded basin to form one of the most prominent topographic features in the country - the rim rocks. Away from the crest, the Eocene beds are overlain by flat-lying sediments of Miocene-Pliocene (?) age (the Neogene Complex), clearly suggesting that folding of Bahrain Dome pre-dates the deposition of the Miocene beds. In the marginal areas, the Pliestocene - Holocene deposits overlie the older units with a pronounced unconformity, confirming the existence of the Post - Dammam local and regional uplift. On the crest of the domal structure, erosion remnants of a massive blanket of dolomitic limestone and coral-bearing limestone, of presumably Miocene age (Jabal Cap Formation), rest unconformably on the Middle Eocene rocks. The generalised geology of Bahrain is illustrated in Figure 2.8.

The initiation of the Arabian Anticlines is not well understood, and is still a matter of debate. There are reasons to believe that they are formed in response to horst-like basement uplifts (Powers *et al.*, 1966; ARAMCO, 1975; Chapman, 1973). The Bahrain and Dammam Domes are believed to be a result of deep-seated Infra-Cambrian Hormuz Salt diapirism (Willis, 1967; Kent, 1978; Samahiji and Chaube, 1987), from their oval shapes and strong negative gravity anomaly. With regard to the Bahrain Dome, however, the steeper western flank would suggest that compressive forces have also been active to a small degree (Willis, 1967; Messrs Sandberg, 1975; Larsen, 1983).

Figure 2.8 Generalised geology of Bahrain (slightly modified after GDC, 1980b)



Kassler (1973), states that the Arabian folds' growth, including growth of the Bahrain Dome, have two striking characteristics: prolonged structural growth dating perhaps as early as the Permian time and lasting well into the Tertiary, accompanied by upward movement during sedimentation and low vertical relief. In contrast to his final conclusion, Samahiji and Chaube (1987) documented relatively high vertical relief, which reaches some 1181 m at Khuff (Tatarian - Kazanian) level. Detailed stratigraphic studies of the Fars Platform in Iran suggests that the Hormuz Salt started to migrate upward during the Late Jurassic and first surfaced in the Early Cretaceous (Kent, 1979; quoted in Weijermars, 1999). de Mestre and Hains (1958) conclude that the principal uplift that led to the present structure of the Bahrain anticline appears to have occurred in the Late Miocene, and since that time further structural growth has occurred, though at a reduced rate. Samahiji and Chaube (1987) suggested a tectonic history of Bahrain Dome growth as follows:

- Slow but steady growth through the Upper Jurassic - Lower Cretaceous.
- Accelerated growth through the Upper Cretaceous culminating in the Turonian.
- Continued growth through the Santonian - Maestrichtian (Aruma Formation).
- Strong growth through the Eocene continued probably to the Miocene.

The Tertiary rocks of Bahrain that form the dome are unfaulted at outcrops, but evidence of faulting is discernible at shallow levels in the Cretaceous Formations from the detailed mapping of oil companies. Most of the faults observed in the subsurface have displacements of less than 15.2 m, and all are classified as normal tension faults (Willis, 1967). Several synclinal flexures developed due to subsidence along these shallow seated normal faults. The majority of these synclines trending NE-SW, oblique to the axis of the main dome, and, because of their flat-lying beds in the cores, are interpreted as being the surface expression of shallow faults and probably pre-date the development of the main dome (Doornkamp *et al.*, 1980). Six low amplitude synclinal wraps have been identified on the Dammam dipslope (Brunsden *et al.*, 1976b). Only three of these are well developed (Al-Hassay, Ras Hayyan, and Ad Dur Synclines) (see Figure 2.8).

Joint traces, predominantly of NNW-SSE trend, and karst enlargement features can also be observed on the Dammam dipslope (along the Khobar escarpment faces). These joints, according to Larsen (1983), are principally extension and vertical joints that have been formed due to slight elongation of rocks during folding, and are closely related to the major folding during the Late Miocene - Pliocene (the Zagros orogeny). These joints and fractures, which are believed to be responsible for the remarkably large number of natural springs in Bahrain, have significant control not only upon the transmissivities of the aquifer systems, but also on their salinity distribution because they serve as conduits allowing groundwater to migrate between the aquifers. In many cases, however, jointing, fracturing and bedding features on the Dammam dipslope are partially masked by the duricrust (caliche) coating (Messrs Sandberg, 1974).

Various minor shallow-seated flexures are imposed on the major structure and are generally regarded as due to slumping consequent upon the removal and solution of the anhydrite from the Lower Eocene - Rus Formation (Wright, 1967). The Post - Dammam uplift, as reported by Willis (1967), made possible the leaching of the evaporites from the Lower Eocene section, causing slumping along the structural axis. Over the crest of the dome, and for some distance down dip, there is no anhydrite remaining in the Lower

Eocene, but further down dip, particularly on the northern plunge, a considerable aggregate thickness of anhydrite is developed (Godfrey, 1948). Perhaps, most of the topographic depressions represent the surface expressions of major collapse zones associated with these non-tectonic structures. It is also probable that the development of fracturing and karstification within the Paleocene - Eocene Formations has some links with these collapse structures.

In the north west of the main island, near the Hamala Camp, reversal of regional dip is noticeable at surface along an east-facing escarpment of north-south trend (Figure 2.8). The scarp is developed in the upper Dammam rocks, and can be traced south and north up to the Karzakan and Al-Hajar villages, respectively. In the sub-surface, the scarp is thought to be coincident with a shallow-seated monoclinal flexure or a shallow fault affecting the Dammam and probably the Rus rocks (GDC, 1980b). Subsurface evidence, including geophysical logs and drilling information suggests possible solution collapse features caused by partial or, in places, wholesale removal of the Rus evaporites. Undercutting of softer sediments (chalky limestone) at depth is also possible. This phenomenon has resulted in slumping of the superjacent Dammam strata.

South of Saar village, as shown in Figure 2.9, vertical displacement in the Khobar section of up to 10 m has been identified, indicating slumping or fault movement caused by dissolution of the Rus anhydrite (GDC, 1980c). Similarly, the cross section in Figure 2.10, which explains the development of the shallow structure along the upper Dammam scarp line in Hamala-Dumistan area (Al-Lawzi), indicates rock adjustment accompanied by fault movement, probably associated with the evaporites removal. The northern extension

Figure 2.9 Schematic cross section showing the slumping feature south of Saar village

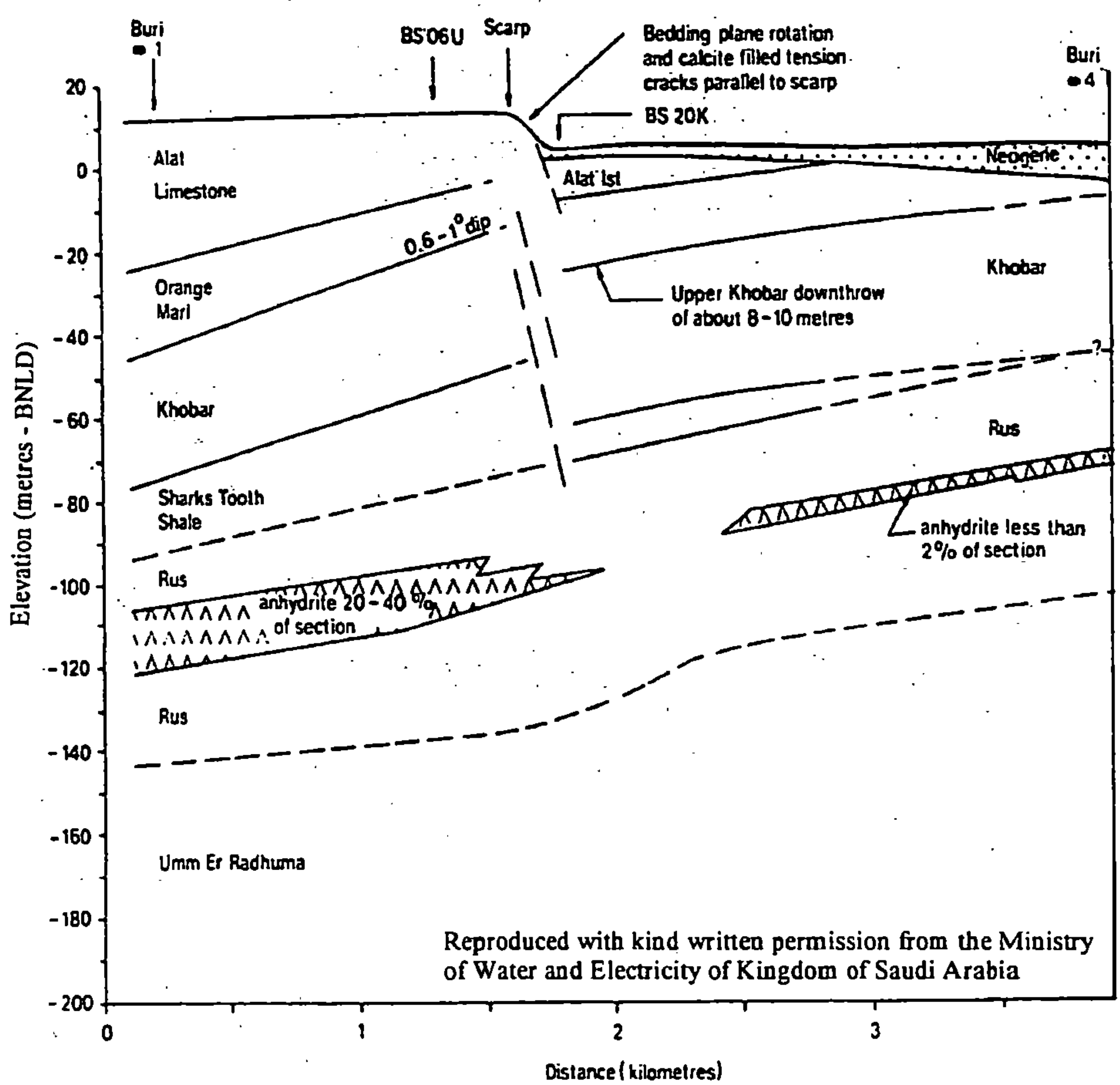
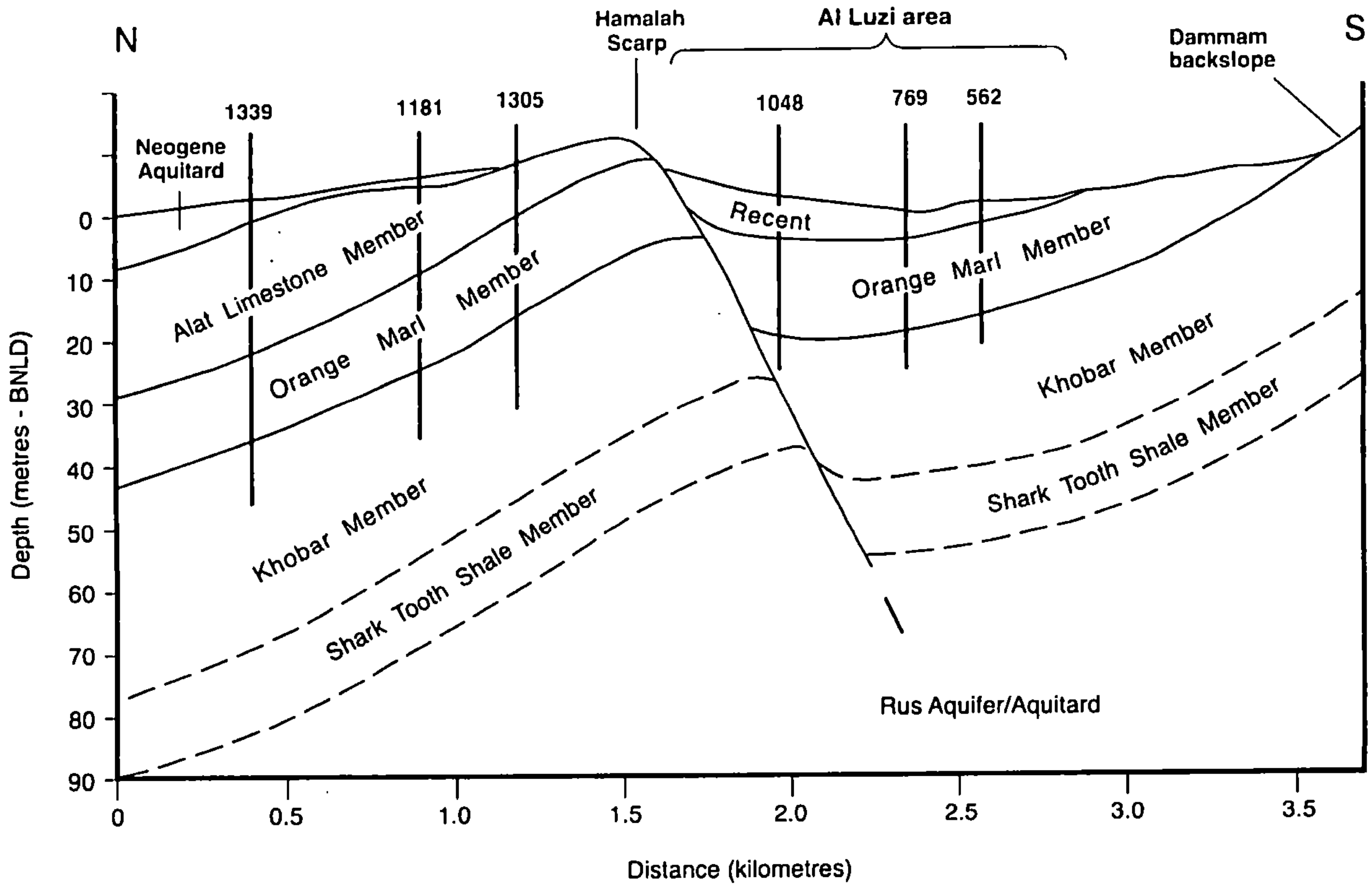


Figure 2.10 Schematic geological cross-section showing the shallow geologic structure at Al Luzi area



of the escarpment continues as far as the Al-Hajar village, swings eastwards across Al-Sehla, Jid Haffs, Al-Khamis, and continues up to the south west of Manama. Along this line, particularly near Al-Hajar and Al-Sehla, slumping of the shallow formations is evident (see the cross-section Figure 3.3 in Chapter Three). This non-tectonic structure, which is known as Al-Hajar Slumping Feature, is also well demonstrated by Gulmon's cross section of 1941, and has exerted a marked influence on the groundwater flow regime and salinity distribution in these areas.

East of Muharraq Island near the town of Al-Busaiteen, localised slumping of the Dammam strata (the so-called Al-Busaiteen Slumping Feature) is feasible at shallow depth (see the cross- section Figure 3.4, Chapter Three). This feature also has a direct bearing on the salinity and hydraulic properties, and geometry of the Dammam aquifers in the area, particularly with respect to the salinity of the Alat Limestone aquifer. Although the structural drilling in north Muharraq and in the north Bahrain Al-Jarim area (see Figure 2.1) showed considerable amounts of anhydrite in the Rus section, Bramkamp (1942) suggested modification of the shallow structure in these areas, claiming that solution subsidence appears to be an adequate explanation for this modification.

2.4.3 Stratigraphy

The Lower and Middle Eocene carbonate rocks represent the majority of rock types exposed in Bahrain, with Miocene and younger rocks occupying the marginal areas (see Figure 2.8). Quaternary sediments dominate the coastal areas, and form extensive coastal plains, particularly in the southern and southwestern portions of the main island. Eocene and Miocene rocks are also exposed in Hawar Islands, while the other small islands of the

Bahrain group together with the patches and shoals are limited to the Pleistocene - Holocene sediments, with the exception of Umm Nassan Island which appears to have some Miocene deposits (Willis, 1967).

The younger units are characteristically unconsolidated aeolian quartz sands, sabkha deposits, and elevated beach platforms of mainly gravels and shell-rich limestone. The rock types within the Miocene are chiefly dolomitic limestones, quartz limestones and calcareous claystone. The Eocene consists of limestones, dolomitic limestones and dolomites, with subordinate shales and marls, and occasional silica growth. Chalk dominates the uppermost of the Lower Eocene, and is also present in several horizons within the Middle Eocene rock units. Evaporites (gypsum and anhydrite) are developed in irregular amounts throughout the Lower Eocene section. The generalised stratigraphic sequence of the Tertiary and Quaternary successions in Bahrain, which represent the stratigraphic range of major hydrogeological interest to this study, and their hydrogeological significance has been summarised in Table 2.19.

The following is a brief discussion of the surface geology of these formations, in chronological order from the youngest to the oldest formations, and is based mainly on the stratigraphic nomenclature and classification proposed by Willis (1967). This is because the adopted lithostratigraphic system is more appropriate to relate to the hydrogeology of the study area, and to the geology in its regional scale. For the Post-Dammam sequence, however, the formal names suggested by Brunsden *et al.* (1976b) in their newly proposed stratigraphic system have received general acceptance. The main feature of the later stratigraphic system, which will be briefly described in the sections that follow and,

Table 2.19 Stratigraphic sequence of the Tertiary and Quatern ary Periods in Bahrain and their hydrogeologic significance

Geological Period	Geological Epoch	Formation	Member	Lithology*	Thickness* (m)	Hydrogeologic significance
Quaternary Period	Holocene	Superficial deposits		Aeolian unconsolidated, commonly calcareous sands. Heterogeneous assemblage of scattered sand dunes, extensive sabkha deposits, and gravels. Abundant alluvial fans, and playa deposits.	Considerably variable, but generally less than 15m	Unsaturated
	Pleistocene	Ras Al-Akur Formation		Limestone,quartozize and oolitic, with massive dolostone and calcisiltite. Dominantly, raised beaches of shelly or coquina-like limestone. Locally, cross-bedded calcareous sandstone or sandy limestone.	4 - 6	Generally unsaturated

Table 2.19 (Continued)

Geological Period	Geological Epoch	Formation	Member	Lithology*	Thickness* (m)	Hydrogeologic significance
	Miocene - Pliocene	Jabal Cap Formation at surface and Dam equivalent at subsurface		Bioclastic massive dolomitic limestone, with stromatolitic limestone. Rare, sandy marl or marly limestone. Dominantly, repetitive series of calcareous claystone and dolomitic limestone at near surface and subsurface, grading to sandy limestone and calcareous sandstone basely.	2 – 60 Much thicker in the northern offshore area	Unsaturated at type locality. Generally, aquitard confines the Alat Limestone aquifer in the coastal areas. In places, the basal sandy limestone forms aquifer with limited productivity, supplying many of the shallow hand dug wells. This layer is usually considered as part of the Alat aquifer, and referred to as the White Limestone.

Table 2.19 (Continued)

Geological Period	Geological Epoch	Formation	Member	Lithology*	Thickness* (m)	Hydrogeologic significance
			Alat Limestone Member	Limestone and dolomitic limestone, highly fossiliferous, slightly porous, and partially limonitic, grading downwards to chalky dolomitic limestone.	15 - 40	Aquifer. Yields moderate supplies of water to wells. In areas has generally low productivity. Locally known as Aquifer Zone "A". Confined and reasonably productive in the northern, western, and northeastern coasts. Is under water table condition in Saar, Janabiya, and parts of Hamala areas, and partially saturated. Absent at the crest of the dome, and around the rimrocks.
		Dammam Formation	Orange Marl Member	Marls, slightly dolomitised, and limonitic. In places, blue – gray and brown marl / shale.	9 - 15	Aquitard confining the Khobar aquifer and separating the Dammam aquifers. Occasionally, loss its effectiveness as aquitard and allows hydraulic connection between the aquifers. Absent at the crest of the dome and most of the central portions.

Table 2.19 (Continued)

Geological Period	Geological Epoch	Formation	Member	Lithology*	Thickness* (m)	Hydrogeologic significance
	Middle Eocene		Khobar Member	Limestone, dolomitic limestone and flint – bearing dolomite, crystalline, fossiliferous, highly, fractured, and mainly hard, and commonly vugy, with frequent silica growth. Locally, containing pockets of gypsums and calcite. Grades to dolorenite / calcarenite facies, and nummulite– bearing limestone, with basal marl.	20 - 45	Excellent aquifer. The main aquifer unit in Bahrain. Highly transmissive and fissured at the upper part. Circulation fluids normally lost at this part of the aquifer. Locally termed as Aquifer Zone "B". Basely, becomes marly and less permeable. Confined at the northern, western and northeastern parts. Unconfined in Buri, Aali and Isa Town areas. Unsaturated in most of the south-central area. Highly salinised in the eastern and north-central parts. Absent near the crest of the dome.

Table 2.19 (Continued)

Geological Period	Geological Epoch	Formation	Member	Lithology*	Thickness* (m)	Hydrogeologic significance
Tertiary Period			Shark Tooth Shale Member	Shale and claystone, subfissile and commonly pyritic. Occasionally gypsiferous, with sporadic dolomitic shale and argillaceous dolomite.	8 - 20	Aquitard confines the Rus - Umm Er Radhuma aquifer, but less effective when reduced in thickness and/when contains dolomites and shally dolomite in relatively large amounts.
	Lower Eocene	Rus Formation		Chalky limestone, dolomitic limestone, with subordinate calcarenite, with some shale and claystone. Irregular development of evaporites (gypsum and anlydrite). Common quartz geodes.	60 - 140	Aquifer or aquitard depending on the presence/ percentage of the evaporites and shale in the section. When becomes non or less evaporitic, it forms together with the underlying Umm Er Radhuma very good aquifer in terms of productivity, but of poor quality. Locally forms limited perched fresh water body. Tapped by a few hand dug wells in the Central Basin. Aquitard when largely consists of anhydrite and shale.

Table 2.19 (Continued)

Geological Period	Geological Epoch	Formation	Member	Lithology*	Thickness* (m)	Hydrogeologic significance
	Lower Eocene – Paleocene	Umm Er Radhuma Formation		Not exposed at surface. At subsurface, highly vugular dolomitic limestone and dolomite. Predominantly calcarenite at the middle part, granular, rarely bituminous, and commonly fossiliferous. Becoming increasingly argillaceous dolomitic limestone, and limestone downwards.	160 - 350	The upper part of Umm Er Radhuma is in hydraulic continuity with the Rus Formation. When the later is non-evaporitic, they form together the so-called Aquifer Zone "C". Present everywhere under Bahrain surface, and is mainly confined. Highly fissured and transmissive, but generally less important owing to its high salinity and presence of hydrogen sulphide. Salinity stratified, basely contains connate water.

*Including surface and subsurface.

whenever necessary, compared with the adopted system, is that it promoted the Eocene rocks (Dammam and Rus Formations) to a group status, with detailed sub-divisions based on stratigraphic, paleontological, and depositional grounds. Table 2.20 is a lithostratigraphic comparison between the stratigraphic nomenclatures adopted for the present study and that proposed by Brunsden *et al.* (1976b), produced together with a lithostratigraphic correlation between the Tertiary and Quaternary periods in Bahrain and their equivalents in Saudi Arabia mainland and Qatar Peninsula.

It perhaps worth mentioning that because of security reasons, lack of authoritative permission inhibited carrying out an extensive geological field check. Moreover, many of the geological sites of interest are now under military restrictions. The at-shallow depth lithostratigraphy of the Tertiary and Quaternary formations is treated in the next chapter; however, subscrop characteristics will be touched upon when the need arises for the sake of completeness.

Pleistocene - Holocene Deposits

The Holocene in Bahrain is represented by flat-lying detrital materials forming extensive coastal plains, beach ridges, isolated sand dunes, and basins fill (playa deposits). These sediments are primarily composed of sabkha deposits, unconsolidated superficial materials of gravel, sand and silt, and shell rich beach limestone (skeletal or coquina-like limestone). Tidal mud-flats and marshes (sabkha deposits) of presumably Holocene age occupy most of the southwestern and southern coasts across Al-Jazair to Al-Mummatallah. Similar deposits are also found in the southeastern portions of the study area. The sand and silt materials cover extensive parts of the coastal areas along Ras Al-Bar and Ras Al-Jazair.

Table 2.20 Lithostratigraphic comparison between the Tertiary and Quaternary units adopted for the present work and those proposed by Brunsden et al, and lithographic correlation between these units and their equivalents in Saudi Arabia mainland and Qatar Peninsula

Age	Present Work	Brunsden et al. (1976) [2]	Equivalent in Saudi Arabia [3]	Equivalent in Qatar Peninsula [4]
Recent	Superficial deposits - Unnamed.	Superficial deposits - Unnamed	Superficial deposits - No formal name has been given.	Superficial deposits - No formal name has been given.
Pleistocene	Ras Al-Akur	Ras Al-Akur	Bahar Formation (informal)	
Miocene - Pliocene	Jabal Cap Formation at surface - Neogene Complex (Dam equivalent) at subsurface.	Jabal Cap Formation	Dam, Hadrukh and Hofuf Formations	Miocene - Dam and Hadrukh (?) Pliocene - Lower Fars Formation
	Dammam Formation	**Dammam Group**	**Dammam Formation**	**Dammam Group**

Table 2.20 (Continued)

Age	Present Work	Brunsden et al. (1976)[2]	Equivalent in Saudi Arabia[3]	Equivalent in Qatar Peninsula[4]
		Jabal Hisai Carbonate Formation		
		West Riffa Flint Formation (?)		
	Alat Limestone Member		Alat Limestone	Upper Abarug Member
		Al-Buhair Carbonate Formation		
	Orange Marl Member	Not recognized at surface, but possibly encountered within the lower part of Al-Buhair Carbonate Formation	Alat Marl	Lower Abarug Member
	Khobar Member			
	Khobar Limestone and Dolomite		Khobar Limestone	
		AL-Buhair Carbonate Formation		Umm Bab Member
Middle Eocene	Khobar Alveolina Limestone and Dolarenite		Khobar Marl	
		Foraminiferal Carbonate Formation		

Table 2.20 (Continued)

Age	Present Work	Brunsden et al. (1976) [2]	Equivalent in Saudi Arabia [3]	Equivalent in Qatar Peninsula [4]
	Khobar Marl and Limestone		Alveolina Limestone	Dukhan Alveolina Limestone Member
			Saila Shale	Midra and Saila Shale Member
	Shark Tooth Shale Member	Dil Rafah Carbonate Formation		
			Midra Shale	Rujm Ai'd Velates Limestone Member
		Rus Group		
		Hafirah Carbonate Formation	Rus Limestone	
Lower Eocene	Rus Formation		Rus Marl and Limestone	Rus Formation

Table 2.20 (Continued)

Age	Present Work	Brunsden et al. (1976) [2]	Equivalent in Saudi Arabia [3]	Equivalent in Qatar Peninsula [4]
Lower Eocene - Paleocene	Umm Er Radhuma Formation - Not recognised at surface	Umm Er Radhuma Formation - Not seen at surface outcrop	Umm Er Radhuma Formation	Umm Er Radhuma Formation - Not developed at surface

Notes:

1- The present study believes that the Jabal Hisai Carbonate Formation of Brunsden et al. is equivalent to the Alat Limestone Member. The Orange Marl is also represented at the base of this Formation. The West Riffa Flint Formation represents the very top of the Khobar Member (Khobar Limestone and Dolomite). The Al-Buhair Carbonate Formation of Brunsden et al. is more likely equate with the middle Khobar (Khobar Alveolina Limestone and Dolarenite), which also correlate in part with the Brunsden's Foraminiferal Limestone Formation. The Khobar Marl is probably comparable to the Lower part of the Foraminiferal Carbonate Formation. More is said on this during the discussion of the stratigraphy.

2- Slightly modified.

3- After Powers et al., 1966.

4- Slightly modified from Cavelier, 1975.

Subsurface data show that these deposits rest unconformably upon rocks of the Miocene age. Quaternary detrital deposits of superficial sand and silt materials, sand dunes, and alluvial fans cover large areas within the interior basin. These deposits either unconformably overlie the Lower Eocene (Rus Formation) or generally overlap the lower members of the Middle Eocene Dammam Formation.

Along the western and northern coasts of Bahrain, the eastern coast of Muharraq Island, and across the shore of Huwar Island, elevated beach limestone deposits forming beach ridges irregularly overlap the Miocene beds or the top members of the Middle Eocene. They are largely made up of skeletal limestone, shelly calcarenite, shelly gravels, and quartozise limestone. The beach ridges are probably of Late Pliestocene - Early Holocene age, and are presumably equivalent to the Bahar Formation (approximately Lat. 27° 01′ N., Long. 49° 40′ E.) in Saudi Arabia mainland. Ridley and Seeley, (1979) interpret these deposits to have resulted from Late Quaternary uplift of the eastern Arabian coasts.

Brunsden *et al.* (1976b) elucidate the numerous bedrock exposures and the isolated spots at the eastern coast near Al-Akur and Sitra shorelines, and western coast near Al-Jazair as being Pleistocene or Late Pliocene in age from fossil evidence. They are the first to raise these deposits to a formation status and to establish the Ras Al-Ikur Formation as the Pleistocene type locality. As described by Brunsden *et al* (1976b), these deposits are characteristically very pale orange, moderately weathered and frequently oolitic dolosiltite, calcisiltite deposits, overlain by massive, quartzitic and shelly flood plain limestone, with a maximum thickness of about 3.5 m. The accurate age of these deposits, however, has not been definitely proved. While Brunsden *et al.* (1976b) report *Peneroplis* from these deposits, confirming that they are Pleistocene in age, they were previously mapped by Willis (1967) and BAPCO (1974) as Miocene or probably older age.

Outcrops of light-coloured cross-bedded, weakly cemented calcareous sandstone or sandy limestone termed as aoelionite (miliolite) are recognised in several localities in Bahrain, including Jiddah Island, Al-Mummattalah, near Al-Lawzi Lake, and at escarpment along Az-Zallaq Highway. Similar deposits occur as scattered patches filling gaps within the rimrock, and a presumed ancient river channel within the interior basin. In most cases, these deposits rest unconformably on the Eocene beds, but are also seen overlapping younger rocks (presumably of Miocene age) in Umm Nassan and Jiddah Islands. At the later occurrence, the aoelionites overlap the presumed Miocene rocks with strong angular unconformity.

The age of the miliolite in Bahrain is also questionable. The early workers (Willis, 1967; BAPCO, 1974; Pilgrim, 1908) assigned them Miocene age, but Brunsden *et al.* (1976b) limit them to the Pleistocene. On the basis of the stratigraphic relation of these deposits with the underlying strata, particularly in Jiddah and Umm Nassan Islands, and from the close lithologic correlation with the cross-bedded calcarenite described by Holm (1960) in Saudi Arabia mainland, they appear to be much younger than Miocene. Therefore, the later view has received acceptance from the present investigation.

Miocene - Pliocene (?) Deposits

The Miocene in Bahrain has few surface exposures, but borehole evidence shows Miocene lithologies of varying thickness unconformably overlying the Middle Eocene rocks, indicating long and deep erosion of the Post-Miocene rocks over Bahrain anticline. In accordance with Brunsden *et al.* (1976b) interpretation, the light-coloured, massive dolomitic limestone and the stromatolitic/algal limestone sequence that form the summit of Jabal Ad-Dukhan, undoubtedly fall entirely within the Miocene. They argued that these sediments, which have been interpreted by the earlier writers (various unpublished oil companies reports; Willis, 1967; BAPCO, 1974) as an outlier within the Middle Eocene, rest unconformably on the Eocene beds with a basal conglomerate surface. Therefore, the break between the Rus group and the presumed Miocene Japal Cap Formation corresponds to the Pre-Neogene unconformity, implying that they are clearly much younger than the underlying units.

Until further palaeontological evidence is made available, it would be reasonable to accept the Brunsden *et al.* supposition on the basis of the following considerations: (1) the lithologic similarity between these rocks and the well-dated Lower - Middle Miocene stromatolitic limestone identified by Tleel (1973) at the top of the Dammam Dome in Saudi Arabia, (2) their stratigraphic relations with the adjacent strata, and (3) their biostratigraphic correlation with the Miocene beds in Iran and the Middle East recognised by Henson (1950) quoted in Tleel (1973). These deposits were first received their formal name (Jabal Cap Formation) in 1976 by Brunsden *et al.*, who presented a detailed description of this formation as the Miocene type locality. They equate the Jabal Cap Formation with the Lower - Middle Miocene Dam Formation (Burdigalian?), which is named after Jabal al Lidam (Lat. 26° 21´ 42″ N., Long. 49° 30´ 24″ E.) in Saudi Arabia mainland.

Miocene outcrops of cream to tan limestone, with basal marl are also recognised in Umm Nassan Island. Deposits of presumed Miocene age were also seen in Huwar Island overlapping the Middle Eocene rocks. Exposures of what is believed to be of Miocene are identified as isolated bedrocks, south of Ash-Shakhoora, and in the vicinity of Al-Moqsha and Salmabad. Their lithology reflects light cream to off white, highly weathered, often sandy, marl and claystone facies with subsidiary quartz-limestone.

Although, Brunsden *et al.* (1976b) doubtfully mapped part of the Ras Al-Akur Formation as Late Pliocene in age, the Pliocene does not appear to be present at Bahrain surface. It is quite probable, however, that sediments of Pliocene age may be encountered at depth, especially in the northern and southern parts, where the Mio - Pliocene sequence is known to be considerably thickened.

Regionally, the Miocene and Pliocene deposits covers wide areas of the Arabian Peninsula, and are generally identical in lithologic character to those found in Bahrain. In Saudi Arabia mainland, they are represented by the Hadrukh (Lower Miocene) and Dam (Lower - Middle Miocene) Formations. Lithologically, they are chiefly clastic sequence of calcareous sandstone interbedded with marl and clay, with abundant chert bands (Powers et el., 1966; Tleel, 1973; Edgell, 1997). The Pliocene Hofuf Formation (Upper Miocene - Lower Pliocene) is dominantly a complex assemblage of non-marine sandy limestone, sandy marl and marly limestone, with intercalations of conglomerate and chert (Powers *et al.* 1966). In Qatar Peninsula to the east, the Hadrukh Formation is more likely missing, but the Dam is present in the central and southwestern areas, with mainly limestone and marl (Cavelier *et al.*, 1970). The Pliocene there is approximately correlated with the

Lower Fars Formation of Iraq and Iran (Cavelier, 1975, cited in Doornkamp, *et al.* 1980).

The upper contact between the Miocene (Dam equivalent) and the younger formations is probably unconformable, and is normally placed at the level where the loosely cemented calcareous quartz-sand and beach limestone of the overlying Pleistocene - Holocene age above, pass downwards to vari-coloured, calcareous claystone of the Miocene below. The boundary with the underlying Middle Eocene is also unconformable, and is as described in the later section.

Middle Eocene Deposits

The Middle Eocene in Bahrain is represented by the Dammam Formation, which is named for the Dammam Dome (Lat. 26° 19′16″ N, Long. 50° 04′50″ E) in Saudi Arabia mainland. A close lithological and palaeontological correlation between the rocks exposed at the Dammam Dome and the Middle Eocene rocks (dated confidently as Lutetian from fossil evidence) in Bahrain is well documented. The Dammam rocks have wide surface exposures over most of the Bahrain Island, with almost similar outcrop pattern to that of the Dammam dome. These exposures extend for several kilometres without appreciable lateral change in lithology, suggesting consistency in the depositional environment. The lower members of the Dammam Formation are responsible for the present unique geologic configuration of the country. They form the most conspicuous topographic features in the study area (the rimrock and the backslope).

The stratigraphic relation of the Dammam with the underlying and overlying formations is well defined both on lithologic and palaeontologic grounds. The contact with the underlying Rus Formation (Lower Eocene - Ypersian) is conformable, and is delineated by the change in lithology from brown or blue-grey, sub-fissile shale of basal Dammam, to light-coloured, slightly chalky, granular limestone or calcarenite facies of the very top of Rus Formation below. The top is at the unconformable contact with the Miocene rocks, and is picked at the lithologic break from normal non-sandy carbonate facies of the upper most members of the Dammam to somewhat sandy appearance marine carbonate Miocene sediments. In some cases, however, erosion has cut down deep into the Miocene beds, bringing the Middle Eocene in discordant contact with sediments of younger age (de Mestre and Hains, 1958).

In Saudi Arabia, the equivalents of these sediments are normally subdivided into five members, and are well exposed along the flanks of the Dammam Dome, and in the south and southwest of Dhahran City (Powers *et al.*, 1966; Tleel, 1973). Eastwards, in the Qatar Peninsula, the Dammam rocks are also well developed, and are divided into the Lower Dammam and Upper Dammam (Cavelier *et al.*, 1970).

In Bahrain, the Dammam Formation is classified into four distinct members. Listed in descending order, these members are as follows:

- Alat Limestone Member.
- Orange Marl Member.
- Khobar Limestone Member.
- Shark Tooth Shale Member.

Alat Limestone Member

The Alat Limestone takes its name from Al Alat well no.1 (Lat. 26° 27′ 49″ N., Long. 49° 50′ 11″ E.) in Saudi Arabia mainland, where the upper part is exposed at the surface and the lower part is represented at drilled interval from 0 - 67 m (Powers *et al.* 1966). In Bahrain, it crops out in a few localities, including the prominent cliffs along the coast of Huwar Island. Characteristically, the Alat is white to light grey and occasionally off-white, porous, finely crystalline to aphanitic, molluscan-rich limestone, becoming progressively dolomitic and chalky toward the middle and lower parts. The Alat is best exposed at Jabal Hisai near Bahrain Refinery (see Figure 2.8). The lower part of the member can be seen along the westerly edge of the escarpment, and its upper boundary is exposed at the eastern side (Dames and Moore, 1974). The escarpment comprises about 8m of light-coloured, highly fossiliferous, moderately weathered, dolomitised limestone. *Turitella lucina pharaonis*, and *Chama calcareta* have been reported from Jabal Hisai (Cox, 1936).

A prominent Alat scarp varies in thickness from approximately 7 to 12 m, is also well displayed at the northwestern edge of the Dammam backslope in the vicinity of Hamala area. Here, the Alat is generally white and slightly chalky, highly silicified and partially dolomitised limestone, with abundant well-preserved moulds and casts of molluscs. Local silicification of the Alat Limestone resulted in resistant duricrusted surface or calcrete mantle, which possibly aided in the formation of these prominent scarps. Surface exposures of light-coloured medium-textured limestone of presumably Alat age is recognised in the vicinity of Al-Khamis Mosque. This bedrock exposure probably reflects a northeastwards projection of the Al-Hajar Slumping Feature, or may be a result of a localised uplift. Exposures of what may be of Alat age are found as scattered patches in the eastern and northern parts of Bahrain Island. At outcrop, the Alat Limestone is commonly devoid of foraminifera, but well-preserved Dictyoconus aegyptiensis is detected at several drilled intervals (identified by the author from examination of formation sample cuttings).

Doornkamp *et al.* (1980) argued that the Jabal Hisai Carbonate and West Riffa Flint Formations would seem to have no equivalents in the Dammam Dome as Bahrain Eocene succession appears more complete than those in Saudi Arabia mainland. They suggested that the Alat Limestone Member is probably comparable to the upper part of the Al-Buhair Carbonate Formation, although possible correlation with the lower part of the West Riffa Flint cannot be entirely discounted (see Table 2.20). Nevertheless, it seems that, on the basis of the surface and subsurface stratigraphic relationship, the Alat Limestone equates very closely with the Jabal Hisai Carbonate Formation of Brunsden *et al.*

To the west, in Saudi Arabia mainland, the Alat is exposed at the rimrock of the Dammam Dome. It is, however, best displayed in a low hill at (Lat. 26° 19′ 42″ N., Long. 50° 03′ 24″ E.), which is about 9 m of dominantly light-coloured, chalky, dolomitic limestone. In Qatar Peninsula to the east, the Alat Limestone Member is probably equivalent to the upper part of the Abarug Member, which consists mainly of yellowish grey to brown, molluscan-rich dolomitic limestone and calcian dolomite (Cavelier *et al.*, 1970).

The lower contact of the Alat is sharp but conformable, and is taken at the break, where the off-white chalky dolomitic limestone of the lower Alat changes abruptly downwards to yellow-brown and orange dolomitic marl of the Orange Marl Member below. The limestone/dolomitic limestone sequence of the Alat Member above is unconformably overlain by sandy-like facies (calcareous sandstone or sandy limestone) of presumably Hadrukh equivalent (Lower - Miocene).

Orange Marl Member

The Orange Marl Member is typically yellow-brown to orange, commonly iron stained dolomitic marl, with intercalations of marly limestone, and is equivalent to the Alat Marl Member in Saudi Arabia mainland, which is represented by the lower part of the above mentioned hill (designated as the Alat type locality). This member forms topographically low areas, with thickness ranging from 2 to 6 metres. At Jabal Hisai, it is exposed at the foot of the scarp, and occupies most of the floor of the depression west of this scarp. It also crops out as flat surface areas south of the refinery, and in the east near Ras Abu-Jarjur and Ras Hayyan. At the base of the scarp near the Hamala Camp, the yellow-brown and rusty dolomitic marl of the Orange Marl Member can easily be distinguished from the light coloured carbonate facies of the Alat Limestone Member above. However, in places along the scarp, the contact is masked by scree slope covers of the Holocene age. At a small hill between Aali and Buri about 4 metres of pale orange to yellow, non-fossiliferous, dolomitised, and commonly limonite-stained marl of supposedly Orange Marl age is recognised at the surface. Outcrops of the Orange Marl Member are present south of Dar Kulaib and to the east of the Bahrain University Campus, but these are obscured by the overlying Quaternary sand. Projecting through the Quaternary sand deposits in the west coast just east of Zallaq and down up to the Al-Mummattalah, are a few isolated uncertain Orange Marl exposures.

Brunsden *et al.* (1976b) argued that there is no indication of rocks equivalent to the Alat Marl of Saudi Arabia mainland exposed in Bahrain, though they assumed, based solely on lithologic proofs, that the Orange Marl approximately equates with the lower part of Al-Buhair Carbonate Formation. It appears, however, that strong surface and subsurface stratigraphic relations exist to suggest that at least the lower parts exposures at Al-Hisai and Hamala Camp escarpments are unquestionably an Alat Marl equivalent.

In Saudi Arabia, the Orange Marl equivalent member (Alat Marl) is yellow-brown dolomitic marl at type locality. In the Qatar Peninsula to the east, the Orange Marl is probably comparable to the lower part of Abarug Member, which is as described by Cavelier *et al.* (1970), a yellow and white dolomitic marl and clayey dolomitic limestone.

Only the upper part of the orange Marl appears to crop out in Bahrain. However, the sub-surface evidence indicates that the contact with the under-lying Khobar Limestone Member is conformable, and is often placed at the change from orange to ochre-coloured, partially dolomitised marl above, to light brown and buff, crystalline limestone and dolomitic limestone of the Khobar Limestone Member below. In a few places, such as parts of the western coast, the subsurface lower limit of the Orange Marl Member is normally placed at the change from blue-grey and dark brown shale-claystone facies to the Khobar, light brown and buff limestone below.

Khobar Limestone Member

The Khobar Member is named after the town of Al- Khobar in Saudi Arabia mainland (Lat. 26° 17′ N., Long. 50° 13′ E.) on the eastern edge of the Dammam dome (Powers *et al.*, 1966). Rocks of the Khobar have extensive exposures throughout Bahrain, as they form most of the outcrops along the rimrock. Both the top and base of the Khobar are recognised at surface, giving thickness ranging from 10 to 25 m. Characteristically, the exposed surface of the Khobar is white to off-white and light grey, finely crystalline limestone, dolomitic limestone and dolomite, grading downwards to light brown and very pale orange, highly fossiliferous, dolarenite/dolosiltite facies, with marl forming the base of the member.

The Khobar in Bahrain is subdivided into three parts: the Khobar Limestone/Dolomite, Alveolina Limestone, and the Khobar Marl. The upper part of the Khobar (Khobar Limestone/ Dolomite) crops out extensively in several localities, including south of Isa Town, and several road-cuts in Hamad Town. A few good exposures of the Upper Khobar are also noticeable along the Awali - Riffa road, and farther west in the vicinity of Aali and West Riffa. Isolated spots of certain upper Khobar lithology are also form the surface in most of the Riffa and parts of Sanad areas. The upper Khobar lithology is primarily flint-bearing dolomite and dolomitic limestone, grey to off-white and tan, mainly hard, commonly fractured, vugular and gypsiferous along bedding planes and fractures, normally containing pockets and veins partially filled with gypsum and calcite. Extensive chertification occurs along karsitic fractures and veins, especially in the escarpment south of Isa Town.

The Alveolina Limestone (middle Khobar) forms most of the escarpment faces around the enclosed basins and the rimrocks, including the escarpments north of Awali, south and west of Riffa, south of Isa Town, and south of Umm Jaddir. Lithologically, the middle

Khobar is light brown to tan and very pale orange, friable, and foraminifera-rich dolarenite/dolosiltite and calcarenitic limestone facies. It contains a well-preserved faunal assemblage both at outcrop and subcrop, containing foraminiferas and undetermined remains of molluscs and echinoids. A comprehensive fossil list, includes *Alveolina elliptica* var. *fosculina*, *Dictyoconoides cooki*, *Nummulites globulus Leymerie sp*. have been identified at several outcrop levels, and *Alveolina frumentiformis*, and *Praealveolina* have wide occurrence at subsurface. *Orbitoides* and *Nummulites beaumonti* have been reported from the middle Khobar by Brunsden *et al.*, (1976b) and Pilgrim (1908), respectively. The middle Khobar has also yielded some well-preserved molluscs; *Ostrea elegans* var. *exogyroides*, and *Opercula* (Pilgrim, 1908; Cox, 1936).

The Khobar Marl has somewhat less exposure areas, and is best seen at the base of the escarpments at Al-Buhair depression (south of Isa-Town). Here, it is a dominantly yellow and pale orange, extensively weathered, rusty dolomarl and argillaceous dolosiltite, which also contains numerous foraminifera species, with *Nummulites beaumonti* being the most common.

Based on stratigraphic considerations, the upper Khobar is at least equivalent to the West Riffa Flint Formation of Brunsden *et al.* As table 2.20 suggests, both the middle and lower Khobar can be correlated with the Al-Buhair Carbonate and Foraminiferal Carbonate Formations of the Brunsden's stratigraphic system.

To the west, in the Saudi Arabia mainland, the Khobar is sub-divided into three stratigraphic units: the Khobar dolomite, Khobar marl, and Alveolina limestone (Powers *et al.*, 1966). The Khobar member in the Qatar Peninsula has a two-fold sub-division: the Umm Bab and the Dukhan Alveolina limestone (see Table 2.20). In lithology, the Khobar members in those countries are composed primarily of carbonate and marl facies, which are identical in lithologic character and faunal range to the sequence identified in Bahrain (Powers *et al.*, 1966; Tleel, 1973; Cavelier *et al.*, 1970; Smout, 1954).

The base of the Khobar falls at the transition from light coloured, foraminifera-bearing limestone, dolarenite above to yellow and brown, often pyritic shale of the Shark Tooth Shale Member below. At subcrop, where the lowermost Khobar consists mainly of marly facies, it is also possible to draw a clear lithologic distinction between this yellow marl unit and the blue-grey shale of the Shark Tooth Shale Member below. Such lithologic differentiation, however, becomes vague when the top of the Shark Tooth Shale is made up of yellow-brown shale - claystone. The Khobar upper contact with the Orange Marl Member is as covered earlier.

Shark Tooth Shale Member

The Shark Tooth Shale is the basal member of the Dammam Formation. The name is derived from the lowest clay – shale bed, in which fossil sharks' teeth are very common (de Mestre and Hains, 1958; BAPCO, 1974). On outcrop, it is generally regarded as the first shale unit below the *Orbitoid* bed. This member is exposed along the base of the rimrock where it forms important marker zone for geological mapping. The best exposures are those located south of Umm Jaddir (near oil well no. 4, 523736 UTM Grid) and at an escarpment further north in the vicinity of Al-Raffah (Sakhir area). The later escarpment was designated by Brunsden *et al.* as the Shark Tooth Shale equivalent

(Dil'Rafah Carbonate Formation) type locality as already demonstrated in Table 2.20.

At these exposures, the Shark Tooth Shale is chiefly yellow-brown, sub-fissile, thinly laminated, often pyritic and gypsiferous shale/claystone, with frequent impure beds of white to pale orange, slightly dolomitised limestone. In places, such as the escarpment at Al-Hunainiah depression, the member contains grey to greenish grey, dolomitic shale or shaley dolomite, with common nodular pyrite. Cox (1936) reported the occurrence of well-preserved specimen of *Ostrea turkestanensis* from the lower part of the member, and the thin limestone unit yielded *Nummulites globulus* (Pilgrim, 1908). Oyster shells have been reported from the Dil'Rafah Carbonate Formation of Brunsden *et al.* Abundant fossil sharks' teeth, echinoid spines, and other undetermined fossils recovered from the weathered surface of the lower shale unit, particularly at the escarpment near oil well no. 4.

The Shark Tooth Shale Member in Bahrain is comparable in age with the Midra Shale Member in Saudi Arabia mainland, which is mainly yellow-brown shale-claystone and grey marl at the type locality. In the Qatar Peninsula, the Shark Tooth Shale equivalent is the Midra and Saila Shale Member, which is principally a yellow-brown to greenish grey, commonly pyritic, attapulgite-rich shale, with frequent occurrences of thin, impure limestone and dolomite beds (Cavelier *et al.*, 1970).

The Shark Tooth Shale contact with the underlying Rus Formation is conformable and is taken at the level where the yellow-brown, sub-fissile shale-claystone is sharply underlain by white, microcrystalline, often siliceous chalky limestone. In the scarp along Umm Jadir

Catchment, however, this contact is usually difficult to identify owing to the relatively thick wadi fills cover.

Lower Eocene Deposits

The lower Eocene deposits in Bahrain are represented by the Rus Formation. This formation is named for Jabal Umm Ar Ru'us (Lat. 26° 19′ 30″ N., Long. 50° 10′ 00″ E.), a small hill on the south eastern flank of the Dammam Dome in Saudi Arabia, where the type section is defined (Powers, *et al.* 1966). The Rus Formation is commonly unfossiliferous, but from its stratigraphic relation with the underlying and overlying formations that have been well-dated palaeontologically, it is clearly Lower Eocene Ypresian in age. The oldest rocks cropping out in Bahrain belong to the upper part of the Rus Formation, although some workers (Italconsult, 1971; Larsen, 1983) believe that the uppermost part of the underlying Umm Er Radhuma Formation might be present at the surface in Bahrain.

The Rus Formation floors substantial areas of the interior basin and also occurs as wadi floors in some of the depression areas, plus forming numerous small hills within the basin itself. A very good exposure of the uppermost Rus, possibly Hafirah Carbonate Formation of Brunsden *et al*, is seen along the base of the south eastern rimrock, where (according to Willis, 1967) a dolomitic chalk bed about 3m thick extends for a considerable distance. The lithology is dominantly white to off white and sometimes tan, slightly dolomitised chalky limestone, dolomitic limestone and dolosiltite, with abundant quartz geodes. The quartz geodes pave extensive areas of the interior basin surface. Such occurrences may indicate that the geodes, which normally fill the solution cavities in the calcareous materials, are diagenetic in origin and are formed by replacement of calcium carbonate by silica. These geodes are probably left behind after erosion of the relatively softer carbonate sediments. Evaporites (gypsum and anhydrite) and shale were not recognised at outcrop, but known to exist widely at depth.

Brunsden *et al.* (1976b) raised the Rus Formation to a group that includes two formations – the Awali Carbonate, and the Hafirah Carbonate Formations. This subdivision is based on the occurrence of hard surface at the upper most layer of the Awali Carbonate bored by crustaceans and *Lithophaga*-type molluscs. They assumed that deposition ceased and the surface sediments of the Awali Carbonate became lithified shortly after their formation. The Hafirah Carbonate is equated with the chalky limestone of the Rus Formation, while the Awali Carbonate correlates with the variable marl and limestone member of the Rus.

In Saudi Arabia mainland, the Rus is usually subdivided into three or four units, and is typically chalky limestone, and light coloured marl and shale, with abundant quartz geodes (Powers *et al.*, 1966; Tleel, 1973; Weijermars, 1999). It is exposed in a narrow outcrop for some 180 km northward of Wadi Al-Sahba, and as a nearly circular outcrop some 10 km in diameter in the breached core of the Dammam Dome (Edgell, 1997). The general sequence of the Rus Formation in the Qatar is characterised by a lower dolomitic unit, middle evaporite unit, and an upper chalky limestone unit (Whittle and Alsharhan, 1994), with intercalation of greenish grey clay beds (Cavelier *et al.*, 1970).

The base of the Rus Formation is not exposed at surface in Bahrain. Subsurface data, however, indicate that the lower contact with the underlying Umm Er Radhuma

(Palaeocene - Lower Eocene) is conformable. Yet this contact is not simple to pick on lithologic grounds, because the normally olive green to grey and light brown, granular, often siliceous and friable calcarenite and dolomitic limestone of the Lower Rus normally extends down without interruption to the olive green and brown dolomitic limestone or calcarenitic limestone of the presumed uppermost Umm Er Radhuma Formation.

In a few cases, however, where the Lower Rus is composed of light-coloured, chalky dolomitic limestone and calcarenite facies, the contact is arbitrarily fixed at the colour change. Palaeontologically, subsurface distinction between the two formations is usually made on the basis of the first occurrence of the Umm Er Radhuma marker *Lockhartia hunti* var. *pustulosa*, which often appears below the probable contact (ARAMCO, n.d.; GDC, 1980b). It should be noted, however, that in most of the cases *Lockhartia hunti* is difficult to detect making precise boundary determination somewhat impossible. The upper limit of the Rus Formation is marked by shale and claystone of the basal Dammam as described earlier.

Palaeocene - Lower Eocene Deposits

The Palaeocene - Lower Eocene (Montian? - Thanetian) deposits in the study area are represented by the Umm Er Radhuma Formation, which was named for the Umm Radhmah water well (Lat. 28° 41´N., Long. 44° 41´E.) in Saudi Arabia mainland. The age of the Umm Er Radhuma has been determined as Palaeocene - early Lower Eocene from a fossil-dated subsurface (Tleel, 1973). Surface exposure equivalent to Umm Er Radhuma has not been recognised in Bahrain, though Italconsult (1971) suggests that a few limited outcrops are probable in the central part of Bahrain anticline. It appears, however, that there is no lithological or palaeontological evidence to support this view.

The Umm Er Radhuma deposits are present everywhere below the surface of the study area, and are predominantly a sequence of dolomitic limestone, calcian dolomite and calcarenite becoming increasingly argillaceous downwards. Microfossil assemblages of, for example, Globorotalites, Anomalina, Globanomalina sp., Lockhartia haimi, and various Ostracods species have been reported by GDC (1980b) from the Lower Umm Er Radhuma.

It has been demonstrated (Powers *et al.*, 1966) that the Umm Er Radhuma has wide surface exposures in Saudi Arabia, and is everywhere a repetitious series of light-coloured, locally silicified, and foraminiferal dolomitic limestone, dolomite and calcarenitic limestone. Exposures belonging to Umm Er Radhuma have not been recognised at the surface of Qatar Peninsula, but deep holes suggest a predominantly dolomite and dolomitic limestone, often fossiliferous and containing chert and clay bands (Cavelier *et al.*, 1970).

The base of Umm Er Radhuma is at the disconformable contact of grey to greenish grey, argillaceous limestone and shale of the uppermost Aruma Formation (Upper Cretaceous) below, with the Umm Er Radhuma dolomitic limestone, cream to brownish grey, and commonly fossiliferous above. The upper contact of the formation is conformable, and has already been described in connection with the discussion of the Rus Formation.

2.4.4 Depositional Setting

Generally, the depositional environments in the Arabian Peninsula were dominated by carbonate sedimentation on a stable and broad shelf, which formed part of the Tethys sea (Powers, *et al.* 1966). In Bahrain, the depositional history of the Tertiary may be characterised by presence of two sedimentary cycles, separated by a major regional unconformity during the Upper Eocene and Oligocene time (the Pre-Neogene Unconformity). These sedimentary cycles are as follows:

- The Palaeocene - Middle Eocene cycle, marked by widespread transgression, resulted in deposition of predominantly carbonates and evaporites in shallow marine to restricted marine (lagoonal) environments.

- The Miocene - Recent cycle, characterised by sequential transgressions and regressions phases, during which a mixture of shallow marine, tidal-flats and continental conditions prevailed.

The deposition of dominantly shallow marine carbonates and clastic sediments during the Upper Cretaceous time (Aruma Formation - Campanian through Maestrichtian) had been followed by tectonic development during the Upper Late Cretaceous time (Powers *et al.*, 1966). This has marked the onset of major orogenic movements in the area, and resulted in widespread emergence over many parts of the Arabian Peninsula, indicating definite disconformity between the Upper Cretaceous and the Palaeocene (Powers *et al.*, 1966).

Tertiary sedimentation started in the Arabian Peninsula with a transgression at the beginning of the Palaeocene when the Umm Er Radhuma Formation of the Palaeocene to early Lower Eocene age was deposited in a shallow marine to neritic environment (Mukhopadhyay *et al.*, 1996). Palaeocene transgression was widespread and resulted in thick successions of neritic limestones and more basinal marls (Powers *et al.*, 1966). In Bahrain, this episode resulted in deposition of generally more than 200 m of shallow water carbonate sediments. Subsurface information suggests that Bahrain, including its offshore areas is completely covered by the Palaeocene carbonate rocks (i.e. it practically occurs under the entire subsurface of the country).

The Ypersian Rus Formation (late Lower Eocene) time has witnessed shallowing upward cyclic sedimentation involving a sequence of regression and transgression episodes. The sea has regressed towards the close of the Umm Er Radhuma time, developing sabkhah or restricted marine conditions over many parts of Arabia (Powers *et al.*, 1966). The base of the Rus, however, still reflects normal marine conditions. Further regression produced conditions favourable for widespread lagoonal evaporites (mainly gypsum and anhydrite) precipitation, and deposition of non-marine claystone/shale in supratidal sabkhah environment. Frequent marine incursions deposited layers of chalky limestone and calcarenitic limestone in a shallow marine, more likely agitated, environment.

The deposition of these sediments marks shallow marine transgression, while the uppermost part of the Rus Formation indicates regressive features, including chert pods precipitated from silica gels in a restricted lagoon (Weijermars, 1999). This is evidenced by the presence of quartz geodes at several horizons within the Rus section. This recurrent emergence has masked much of the original texture of the Rus Formation through dolomitisation, recrystallisation and bioturbation (Tleel, 1973). Apparently, this may explain the paucity of fauna in the Rus Formation compared to the rest of the Tertiary formations in both Bahrain and Saudi Arabia mainland.

The Dammam (Middle Eocene) episode of deposition represents a shifting environment from restricted marine (sabkhah) condition that had prevailed during the Rus time to a normal marine condition. During this episode, shallow marine carbonate sediments were laid down over a slowly growing anticline, with intercalation of argillaceous layers in the lower and middle parts of the formation. The presence of black and brown pyrite in the basal Dammam may reflect residual of the restricted marine environment or possibly local lagoonal conditions. As the Lutetian sea gradually advanced, the restricted marine conditions were totally replaced by open shallow marine environment. This environment then became the habitat of sharks and *Ostrea* (Tleel, 1973). Continued transgression near the end of the Shark Tooth Shale time, resulted in relatively deeper and fresher water, and the ubiquitous deposition of *Nummulites* and *Alveolina* - rich limestone. Houbolt (1957) recognised that the Alveolina indicates water depths of perhaps between 14m to 20m. The abundant occurrence of flint and chert in the upper Khobar reflects marine invasion supplying colloidal silica or a brief regression cycle leaving solution cavities followed by silica migration and precipitation. From its faunal diversity and spacious limonitization, the Alat Limestone was most likely deposited under a typical shallow marine environment, after a probable momentary phase of shallowing (sublittoral environment) with possible fluvial inputs during the deposition of the Orange Marl Member. This has completed the depositional history of the Dammam Formation.

Widespread emergence of the Arabian platform in the Middle Eocene reduced the Tethys to a relic sea, probably much as it is now; and since then emergence has persisted and continental conditions have prevailed over much of Arabia (Powers, *et al.*, 1966). The sea has completely retreated over Bahrain and a period of active subaerial erosion took place during the Upper Eocene and Oligocene times; and since then Bahrain became a land area (Steineke, 1942), with deposition only occurring on the margins. As mentioned earlier, this erosional episode has produced a major unconformity above the Dammam Formation (the Pre-Neogene Unconformity).

Marine transgression during the Lower Miocene marks the transition to more likely shoreline clastic deposition, under which partly continental arenaceous sediments were deposited with a marked unconformity on the Middle Eocene rocks. These facies possibly correlate with the uppermost Hadrukh Formation (Aquitanian to early Burdigalian) or at least early Dam Formation (Late Burdigalian?).

Intermittent flooding of the Dam sea (Lower - Middle Miocene) produced periodic invasions of shallow water and brought about successions of tidal-mud flats and shallow marine conditions. This has deposited a repetitious series of dolomitic limestone and calcareous mud-claystone over a slowly growing structure. The deposition of the carbonate mud-claystone probably reflects tidal-mudflats sheltered condition. This pattern of sedimentation is perhaps identical to the present-day sabkha-forming conditions, which prevail in the southern and southwestern coasts of Bahrain. The deposition of the dolomitic limestone records some deepening to a typical shallow marine or near shore environment.

Irtem (1986), cited in Weijermars (1999), suggested that the stromatolites of the Dam Formation at the Dammam Dome in Saudi Arabia indicate a shallow, subtidal to intertidal environment of deposition. A similar depositional environment is suggested for the stromatolitic/algal limestone of the Middle Miocene Jabal Cap Formation in Bahrain by Brunsden *et al.* (1976b). The conglomerate erosional surface below this formation confirms that the dome structure had been deeply eroded before the deposition of the Jabal Cap. Tleel (1973) believes that the Middle Miocene transgression in the Arabian Peninsula must have started gradually to produce a tidal-flat environment and stromatolitic limestone, then proceeded with shallow marine encroachment that resulted in the deposition of the dolomitic limestone.

The Tertiary deposition was brought to an end with the start of the regional uplift probably in the Late Pliocene and Pleistocene time (Chapman, 1971; Mukhopadhyay *et al.*, 1996). Perhaps it was during the former period that Bahrain anticline took its present shape (Mukhopadhyay *et al.*, 1996) and the Arabian Gulf reached its current form (Larsen, 1983). During this time, subaerial and coastal erosion has prevailed, and most of the Miocene deposits were eroded away. This erosional episode was concluded with a marine transgression probably in the Early to Late Pleistocene (?). Larsen (1983) suggests that an Early Pleistocene sea level, as much as 150 m higher than present, subsequently covered much of the Arabian Coastal plains and left a series of raised beaches at various places along the coast. The shell-rich limestone and calcarenite facies forming prominent raised beaches in Bahrain and Saudi Arabia (Bahar Formation) were possibly a product of this Post - Miocene transgression cycle. It must be stressed, however, that because of its close relation with the sea level changes, the Pleistocene - Holocene paleoenvironment is rather complex and should be interpreted with some care.

The origin of the presumably Pleistocene cross-bedded sandstone (aeolianites) has been the subject of some controversy. Some investigators (Willis, 1967; Brunsden *et al.*, 1976b) believe that they are more likely erosion relics of what was an ancient coastal dune. This view is substantiated by the common skeletal debris and shell aggregates (*Miliola*) that have been found to constitute large amount of these deposits. Others, (Kassler, 1973), suggests that some of these sands may be reworked marine deposits of an intererstadial high sea level. It appears logical to assume that the low angle cross bedding, and the presence of the *Miliola* may indicate that low energy subaqueous current was in action during the deposition of these sediments. This supposition may be further justified by the occurrence of the flute casted aeolianites in Jiddah Island. The aeolianites, which fill what are believed to be ancient streams within the interior basin, are probably the products of sedimentary deposition in high-energy channel-fills or lacustrine bar environments.

Throughout much of the Ras Al-Akur time, the deposition must have been of shallow water to perhaps near the shoreline environment, with relationship to earlier higher sea levels (Brunsden *et al.* 1976b). The mudflood, consolidated beach sand, and the oolitic limestone deposits all are typical of deposition in such environmental conditions.

The inland sabkhas within the interior basin are probably associated with the pluvial-wet phase, and are indicative of isolated lagoonal conditions. This evaporitic phase is possibly the product of interpluvial periods when semi-arid conditions became dominant, although, as suggested by Larsen (1983), evaporite-forming conditions by seawater inflow through Az-Zallaq gap could not be ruled out.

The Late Pleistocene - Early Holocene time had been marked by continental (fluviatile and aeolian) depositional and erosional conditions that produced varieties of channel streams, playas, dunes, and piedmont deposits of gravely sand, sand gravels, and clays and silts. Apparently, these sediments were deposited under arid to semi-arid conditions, similar to the depositional environments prevail in the area up to the present time.

2.5 Land Use

Bahrain has been occupied by man for many centuries and recent archaeological investigations have revealed evidence of several cultural periods spanning five thousand years (Bibby, 1984). The abundance of ancient grave-mounds and archaeological sites provides clear indications of flourishing ancient civilisations. The island has been linked with the ancient Dilmon (Telmon) of about 2000 BC; a lively and prosperous trading centre linking Sumaria with the Indus Valley (Encyclopaedia Britannica, 1992a). Subsequent history included Greek, Harmuz, Portuguese, Ottoman, and British influences; all of which were attracted by trade and the strategic position of Bahrain, and have left some imprint upon them (Brunsden *et al.*, 1979).

Evidence of former extensive cultivation, including abandoned farmlands, ancient irrigation facilities (underground qanat systems), old hand-dug wells and natural springs is widespread. In fact, Bahrain has always been referred to as a well-wooded and agriculturally productive lands, and the up-welling of copious quantities of its fresh water led to an interesting mythology, and to the possibility of agriculture on an otherwise desert island (Bridges and Burnham, 1980).

Because of its strategic position between India, the Middle East and Europe, Bahrain played a vital role as an ancient trade centre. Urban centres, trade activities, including fisheries and pearling were developed near the coastal areas, whilst agriculture was confined to the northern and western parts of the main island, where arable soils and natural springs exist. The importance of Bahrain as a main commercial and shipping centre in the Arabian Gulf has continued up to the present time. Traditionally, the Bahrain economy depended on trade, pearl diving and agriculture until oil was discovered in 1932 (Brunsden *et al.*, 1979). This has largely transformed the economic infrastructure, to a new oil-related economy. In view of the decline in the oil reserves, Bahrain adapted an income diversification policy during the 1980s, in which the emphasise has been to develop the country as financial and banking centre, and to sprout the tourism sectors.

These major and gradual transforms in the economic base have led to marked changes in the land use patterns. At present, settlement, trade, industry and agricultural activities are concentrated in the northern half of the main island and, to a lesser extent, in Sitra and Muharraq Islands. Urban development and commercial and economic activities are centred in Manama (the capital), where Mina Salman, the largest port, is located. The second urban centre is Muharraq where the Bahrain International Airport is situated. Recently, Jid Haffs in the north, Hamad Town and Riffa (see Figure 2.1) in the south of Bahrain main Island have emerged as important urban centres.

The main industries, including refinery, oil port, aluminium, and petrochemicals, ship repairs are accommodated around the eastern, southeastern, and northeastern parts of the study area, mainly around Sitra Island, south of Awali Town, and Hidd Peninsula. An enormous industrial complex is currently being constructed in the Hidd Peninsula to the east of Muharraq island. Agriculture is still confined to the northern and western parts of the main island. Farmlands occupy a narrow fertile strip (the green belt) extending some 7 km along the northern end of the main island, and about 20 km down its west coast from Budaiya village (see Figure 2.1). This green strip has an aspect of great fertility, which contrasts quite starkly with the bare desert appearances of much of the country (Encyclopaedia Britannica, 1992b). The soil textures in Bahrain are primarily sandy with low organic matter contents, high amounts of calcium carbonate and gypsum, and very low water holding capacity (UNEP/ROWA and UNESCWA, 1991). The salinity of the soils in the agricultural areas is very high ranging from 5 – 12 mmohs/cm in saturated extract (M. Al-Sayed, Soil Laboratory, Agricultural Affairs, personal communication).

Sitra Island to the east, and Aali - Salmabad areas in the north-central part of the main island (Figure 2.1), were used to be active agricultural centres; but farmlands there have been abandoned due to deterioration in groundwater quality and salinisation of agricultural soils. Fortunately, some of these lands, particularly in Buri and Aali villages, have been re-cultivated using the available treated sewage water. Unhealthy agricultural lands are found in the northern and eastern parts of Muharraq near Sumaheej, Dair and Arad villages (Figure 2.1). Potentially arable soils exist in and around the central depression; but unavailability of sufficient fresh water precludes any kind of agricultural development.

One of the most special features of the country is the abundance of ancient mounds and archaeological sites. The mounds are ancient graves, dating back to between about 2,500 BC and 1,750 BC (Bibby, 1984), and are mainly accommodated in Hammad Town, east of Aali, and south of Saar villages. These are known as "Dilmun Mounds" and can be seen from aerial view as conical connected hills. Other archaeological sites are also found further to the north near Barbar and Hilat Abd-As Salih villages. The remainder of the country from the south of Awali Town as well as some of the small marginal islands are essentially uninhabited or of limited permanent settlement. This is because of their relatively tough relief, desert or semi-desert nature and absence of fresh groundwater. The former area is either occupied by oil and gas fields or reserved for military purposes.

Generally, the land use patterns in Bahrain can be classified into five main categories; namely, (i) the agricultural lands, (ii) residential and urban centres, (iii) land used for industrial and commercial activities, (iv) the mounds and archaeological sites, and (v) the gas and oil fields. The categories of interest to this research work are the residential, agricultural and industrial categories. Table 2.21 presents the changes in the land use patterns for the period 1956 - 1988. As the table suggests, the residential areas have increased from 12.35 km^2 in 1956 to 91.95 km^2 in 1988, representing 645 % increase. The areas occupied by industrial sites have increased from 2.8 km^2 to 22.70 km^2 during the same period (about 711 %). The agricultural lands, in contrast, have declined by 37 %, from 64.60 to 40.70 km^2. The table also shows that the land in use has expanded from 248.40 km^2 in 1956 to 384.28 km^2 in 1988, at the expense of the total unused land, which had been decreased from 424.05 km^2 to 306.95 km^2.

In Table 2.22 the changes in land use patterns are expressed as a percentage change of the total. Even though the country's total area has been progressively extended by sea reclamation to cope with the increasing demand for lands by different sectors of development, the percentage changes in the main land use categories closely conform with the actual changes in their areas; confirming the major influence of these categories on the overall changes in the land use patterns.

Table 2.21 Change in land use patterns 1956 – 1988

Land use patterns	Change in land use patterns (km^2)				
	1956	1963	1969	1982	1988
Residential & housing	12.35	22.70	32.20	68.60	91.95
Agricultural areas	64.60	64.60	64.60	37.48	40.70
Industrial areas	2.8	3.30	3.90	12.10	22.70
Cultural centres	---	---	---	1.50	8.50
Recreational & open spaces	2.70	2.70	2.70	14.70	24.40
Public utilities	0.05	0.15	0.36	0.95	1.53
Communications, ports & airports	2.0	2.0	2.0	11.85	11.85
Roads	3.10	5.40	6.60	10.60	20.10
Mounds and archaeological sites	11.80	11.80	9.15	8.75	8.20
Special use areas	---	---	---	15.10	32.35
Quarry activity	9.0	9.0	9.0	9.0	8.0
Oil and gas fields	140	140	140	114	114
Total used lands	248.40	261.65	270.51	304.63	384.28
Total unused lands	424.05	410.80	402.94	380.35	306.95
Total area of Bahrain Islands	672.45	672.45	673.45	684.98	691.23

SOURCE: Modified after MOH and UNCHS (1988), Report on National Land Use Patterns 2001, Vol. 1

Land use changes projected for the year 2001 are given in Table 2.23. The table predicts that the residential, agricultural and industrial land uses will expand by 18.5, 42.9 and 58 %, respectively. By the year 2001, the total land in use is projected to increase by 10.4 %, and the total area of unused land to drop by 10.8 %.

Table 2.22 Total percentage changes in the land use patterns 1956 – 1988

Land use patterns	Percentage changes of total				
	1956	1963	1969	1982	1988
Residential & housing	1.8	3.8	4.8	10.0	13.3
Agricultural areas	9.6	9.6	9.6	5.5	5.9
Industrial areas	0.4	0.5	0.6	1.8	3.3
Cultural centres	---	---	---	0.2	1.2
Recreational & open spaces	0.4	0.4	0.4	2.2	3.5
Public utilities	0.0	0.0	0.1	0.1	0.2
Communications ports & airports	0.3	0.3	0.3	1.7	1.7
Roads	0.5	0.8	1.0	1.5	2.9
Mounds and archaeological sites	1.8	1.8	1.3	1.3	1.2
Special uses areas	---	---	---	2.2	4.7
Quarry activity	1.3	1.3	1.3	1.3	1.2
Oil and gas fields	20.8	20.8	20.8	16.6	16.5
Percentage of used land	36.9	38.9	40.2	44.5	55.6
Percentage of unused land	63.1	61.1	59.7	55.5	44.4

SOURCE: Modified after MOH and UNCHS (1988), Report on National Land Use Patterns, Vol.1

Table 2.23 Land use patterns and areas (1988) and projected land use for year 2001 (square kilometre)

Land use pattern	Existing (1988)	Projected increase (2001)	Total area (2001)	Percentage of total (2001)	Remarks
Residential and housing	91.95	17 *	108.95	15.6	Including Zimma Bay reclaimed area.
Agricultural area	38.50	16.5	55	7.9	Assuming that the daily water requirement per hectare is reduced from 66,000 m^3 to 27,500 m^3.
Poultry farms	2.2	---	2.2	0.3	
Industrial areas	22.70	13.20	35.90	5.1	
Cultural centres	8.5	0.5	9.00	1.3	
Recreational	24.4	5	29.4	4.2	
Public utilities	1.53	0.22	1.75	0.3	
Communications	3.8	---	3.8	0.6	
Ports and airports	8.05	0.5	8.55	1.2	
Roads	20.10	0.85	20.95	3	
Mounds and arch. sites	8.20	---	8.20	1.2	
Special uses	32.35	---	32.25	4.6	
Quarry sites	8	---	8	1.2	
Oil and gas fields	114	-14	100	14.3	
Total used lands (existing and projected)	384.38	39.77	424.05	60.8	
Total unused lands	306.95	---	273.75	39.2	
Total area of Bahrain Islands	691.23	---	697.80	100	

SOURCE: Modified after MOH and UNCHS (1988), the National Land Use Patterns Report, 2001. *Does not include private sector housing activities.

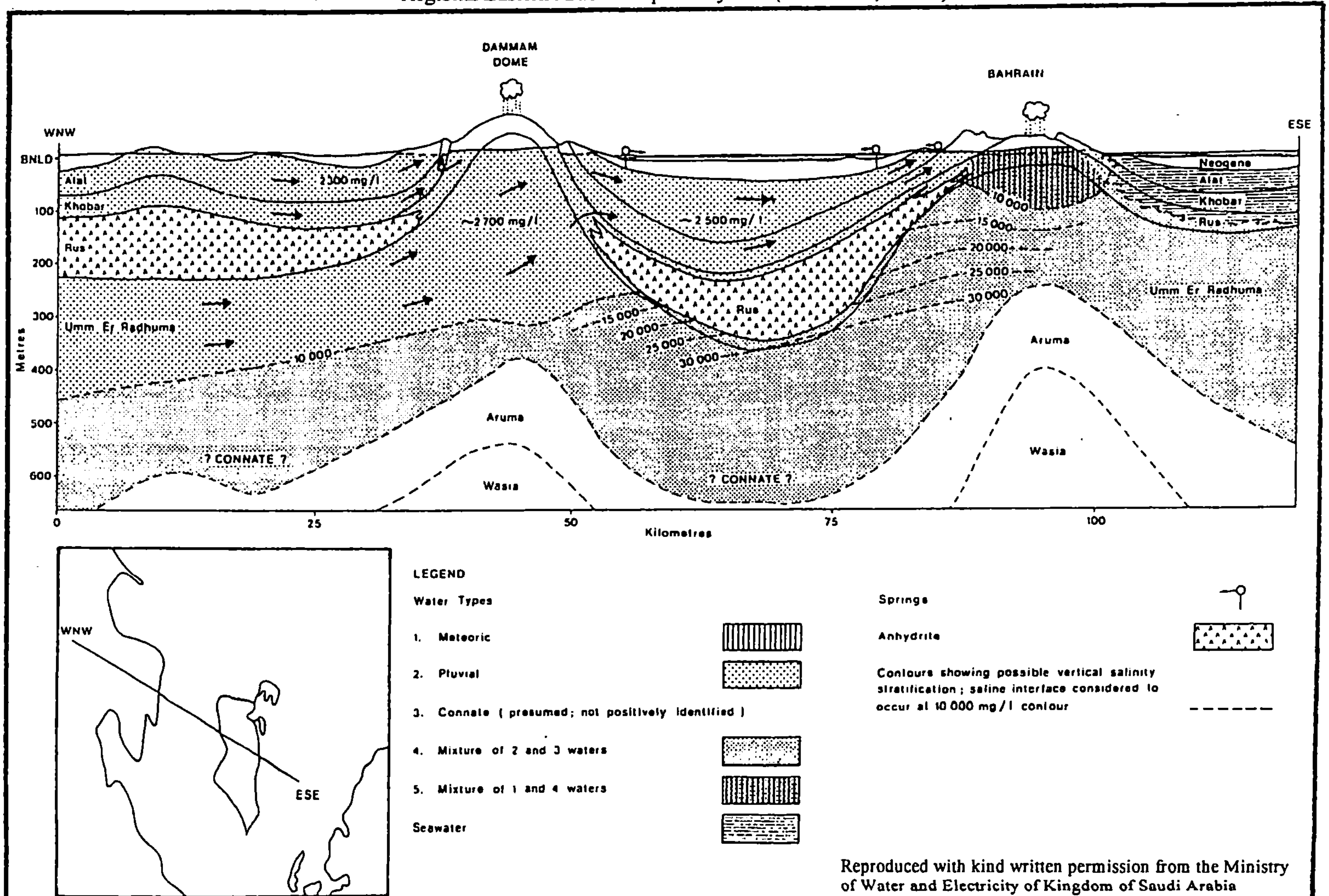
CHAPTER THREE
GROUNDWATER RESOURCES

3.1 The Aquifer Systems

The aquifer systems in the study area are mainly developed in the Tertiary (Paleocene - Middle Eocene) carbonate rocks that are considered part of the Eastern Arabian Aquifer System. This system runs from central Saudi Arabia to the Arabian Gulf waters, where Bahrain is located, and regarded as the major discharge area of the system. These aquifer systems crop out to the west at the Interior Homocline in the Saudi Arabia mainland to receive meteoric recharge (Zubari, 1987). This implies that the groundwater flow regime has a north-west to south-east direction under an eastward dipping hydraulic gradient. Figure 3.1 shows the aquifer systems in the study area, and their hydrogeologic and hydrochemical relations with the regional Eastern Arabian Aquifer System.

The aquifer system in Bahrain consists of three aquifers locally termed, in descending order, as Zones, 'A', 'B', and 'C'. The aquifer Zones 'A' and 'B' are, respectively, developed in the Alat Limestone/dolomitic limestone, and Khobar dolomite/alveolina limestone members of the Dammam Formation, and are collectively termed the Dammam Aquifer System. The Alat is a secondary aquifer, with an average transmissivity of about 350 m^2 day^{-1}, and a permeability averaging about 14 m day^{-1} (GDC, 1980b). It has a normal TDS level ranging between 2,400 – 4,800 mg l^{-1}. In both Bahrain and Saudi Arabia mainland, the Khobar aquifer is divisible into two layers with markedly distinct hydraulic properties. The first layer is developed in the fractured Khobar dolomite/limestone, and hence has high permeability. The second and less permeable

Figure 3.1 Generalised hydrogeological and hydrochemical cross section of the Regional Eastern Arabian Aquifer System (after GDC, 1980b)



Reproduced with kind written permission from the Ministry of Water and Electricity of Kingdom of Saudi Arabia layer is developed in the Alveolina limestone/calcarenite facies. Within the context of this research, the Khobar is treated as a single-layer aquifer. The Khobar is the principal aquifer in Bahrain, providing the country with more than 75 % of its groundwater supply. It has an average transmissivity of around 6,000 m^2 day^{-1}, and a mean permeability of about 314 m day^{-1}. It contains water with a normal TDS concentration of between 2,200 – 4,500 mg l^{-1}.

The Aquifer Zone 'C' is developed in the chalky limestone/dolomitic limestone of the Rus Formation (lower Eocene) and the dolomitic limestone/calcarenite rocks of the upper part of the Umm Er Radhuma Formation (Paleocene - early lower Eocene); and is, therefore, designated the Rus - Umm Er Radhuma Aquifer System. This aquifer system occurs virtually under the whole study area in the form of a large lens, with an average transmissivity of about 14,000 m^2 day^{-1}. It contains brackish water of TDS in the range of 7,000 – 15,000 mg l^{-1} coupled with a marked presence of hydrogen sulphide, which renders it unsuitable for conventional direct use, so it is often used to feed desalination units with their raw water.

A very limited aquifer is developed in the superficial arenaceous sediments of the lower Miocene (Dam equivalent), and is mainly exploited by shallow dug wells. It is very probable that this discontinuous water table aquifer is recharged by percolation of irrigation water and/or by upflow from the Dammam Aquifer System. In a few areas, particularly around the northeastern and eastern coasts, the early Pleistocene algal quartz limestone is commonly envisaged as an upward extension of this aquifer. In the northern and north-eastern portions of Bahrain main island, and in Sitra and Muharraq Islands where the Alat Limestone aquifer is unconformably overlain by a relatively thick argillaceous Neogene cover, the lower part of the Neogene is represented by a thin sandy limestone or calcareous sandstone unit. This unit is termed by BAPCO geologists as the "White Limestone", and - together with the Alat Limestone - forms what is locally termed the Aquifer Zone 'A' (de Mestre and Hains, 1958; Wright, 1967). The Neogene contains water with TDS varying between 2,900 and 5,200 mg l^{-1}.

In the central basin, and in some of the catchment areas within the Rim Rocks, notably in the Ar-Rumaithah, Safrah, Sakhir, and Al-Hunainiah catchments, the unconfined non-anhydritic Rus receives modern recharge by infiltration from rainfall. The rainwater is trapped by impermeable layers to form shallow lenses of limited water perched above more saline brackish water. This perched aquifer supplies a number of shallow hand dug wells, and is partially separated from the Rus - Umm Er Radhuma Aquifer System, and contains water with TDS in the range of 2,000 – 6,000 mg l^{-1}. The salinity of this water, however, tends progressively to increase with depth and continuous pumping.

Brackish groundwater of TDS between 6,000 to 8,000 mg l^{-1} is known to exist in the deep aquifers of the Cretaceous age (Thamama and Wasia Formations – Aptian through Touronian) which are also the major oil producing formations in the country. The salinity of this water is, however, variable and tends to increase with time. For example, very low salinity water of 240 – 520 mg l^{-1} TDS was reported from one well in 1976, but re-analysis in 1978 from the same well showed a salinity of about 8,645 mg l^{-1} TDS (GDC, 1980b). Investigation into these aquifers is beyond the scope of the present research.

3.2 Aquifer Boundaries

Except for the lower Rus boundary, which is somewhat difficult to determine, stratigraphic boundaries of the aquifer systems in the study area are well defined on lithological, palaeontological and geophysical log evidence (GDC, 1980b). On the flanks of the dome, where the full middle Eocene - lower Miocene geologic sequence is present, the Alat Limestone aquifer is bounded at the top by a relatively thick claystone of Miocene age, and at the bottom by the Orange Marl Member of the Dammam Formation. The Khobar is normally confined above by a slightly dolomitised marl and marly limestone of the Orange Marl Member, and below by the shale-claystone sediments of the Shark Tooth Shale Member.

Practically, however, the Orange Marl does not constantly act as an effective aquitard, especially where it thins out or contains significant amount of dolomitic limestone. Rather, it often functions as a leaky confining layer allowing hydraulic connection between the two aquifers. Such a hydraulic connection has been augmented by the traditional drilling practice (before 1980) to open wells into both the Alat and Khobar aquifers. This would mean that hydraulic separation between these aquifer units might be regarded as oversimplification. In some regions throughout the study area, both the Alat and Khobar aquifers are found under phreatic states.

The lower boundary of the Rus - Umm Er Radhuma Formation is marked by the argillaceous limestone and shale of the Lower Umm Er Radhuma - Upper Aruma Formation (Upper Cretaceous). In areas away from the centre of the core, however, the lower Umm Er Radhuma contains highly saline water. The lower boundary of the aquifer may, therefore, be defined by the interface between brackish and highly saline water

(GDC, 1980b; 1983a). The Rus evaporite/shale and/or shale-claystone of the Shark Tooth Shale Member form the upper bounding aquitard of this aquifer system.

As noticed by GDC (1980b), where the Rus has lost its evaporite, particularly in the core region about the oilfield and in the Ali-Salmabad plain, the Rus - Upper Umm Er Radhuma aquifer is bounded above by the Shark Tooth Shale alone, resulting in the aquifer being developed in the residual Rus section and the upper part of Umm Er Radhuma. In very rare cases, the Shark Tooth Shale is absent, and the upper boundary of the system is defined by the free water surface in the Rus formation. Unmodified Rus, with the full section of limestone-claystone-anhydrite forms, together with the argillaceous Shark Tooth Shale, a major system aquitard between the two aquifer systems (GDC, 1980b).

3.3 Aquifers and Aquitards Geometry

The interpretation of the geometry of the aquifer and aquitard units in the study area is based mainly on a number of isopachyte and structure contour maps. The data used to compile these maps were obtained from a comprehensive structural and hydrogeological database, constructed for the purpose of this study, and supported by information derived from BAPCO structural holes. This database, as outlined in Text B-1 of Appendix B, contains information on well locations, construction details, water level and salinity, formation tops, and data on the aquifer hydraulic parameters for some 1,300 water wells. Aquifer and aquitard subsurface lithologic characters have been described on the basis of the author own experience from supervision of borehole drilling and lithological examination of formation cuttings, and by consulting the Bahrain Water Resources Directorate (WRD) borehole files and GDC well completion reports.

Regionally, the disposition of the rock units is controlled by the elevated structural domes of Dammam and Bahrain, their adjacent synclinal or basinal areas and by a flatter, structurally less depressed area to the north-east of Bahrain (GDC, 1980b). As a result of the synsedimentary structural growth, thinning of these units occurs over the crestal regions, while thickening takes place towards the basinal areas (Figure 3.1). Over Bahrain, the Dammam aquifer and aquitard units were eroded away at the crest of the dome during the period of active erosion (the Pre-Neogene Unconformity) to expose the Rus Formation. The older Dammam strata (the Shark Tooth Shale and Khobar members) crop out around the crest of the dome, dip gently towards the west and east, and are overlain in the synclinal areas by the younger Dammam (Orange Marl and Alat Limestone members), and the Neogene and Quaternary sediments (Figure 3.1). As with the outcrop case, the Dammam rocks at subcrop are lithologically homogeneous, with no major facies change (GDC, 1980b).

The Rus Formation crops out at the crest of the dome and thickens towards the marginal areas, while the Umm Er Radhuma Formation does not have surface outcrop, but has undergone depositional thickening away from the Bahrain core. This implies that the deeper formations follow the same structural patterns and thickness configuration.

Schematic hydrogeological cross-sections through the study area are shown in Figures 3.3 to 3.5, with the lines of the sections given in Figure 3.2. The lines of the sections were carefully chosen to demonstrate most of the main geological and structural features such as the Bahrain Dome, including the outlier of Jabal Ad-Dukhan, the rim rocks and backslope, and the main slumping features at Saar, Hajar and Busaiteen areas.

Figure 3.2 The lines of the schematic hyrogeological cross sections

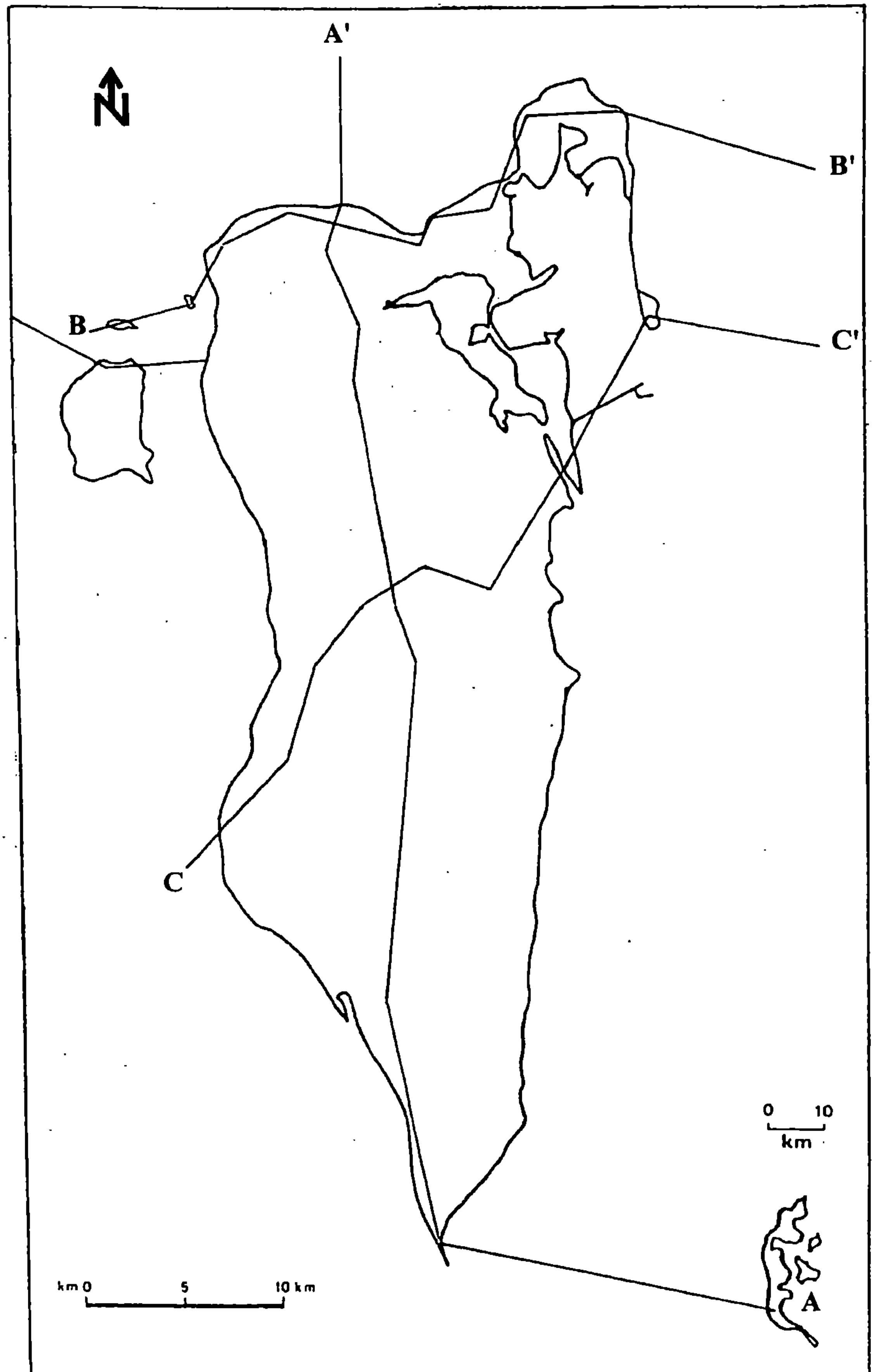
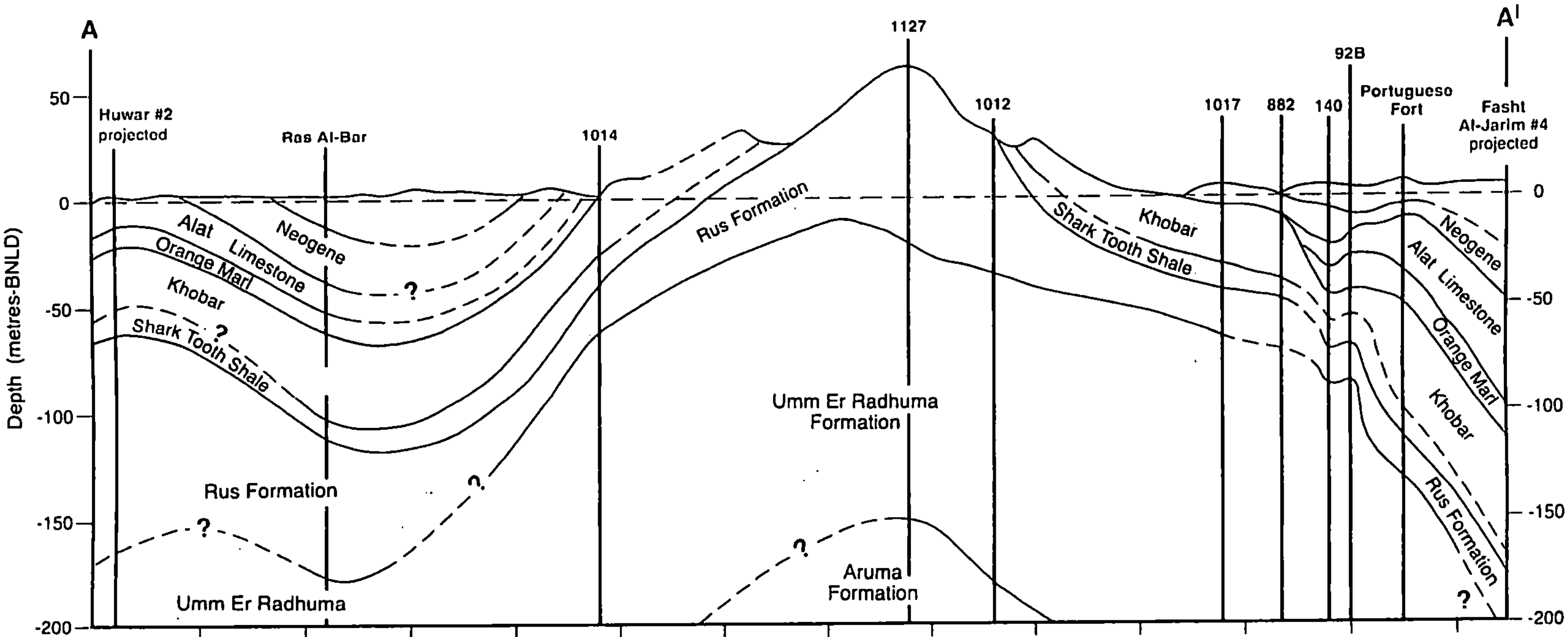


Figure 3.3 Schematic hydrogeological cross-section A - A^{l}



Horizontal scale 1:250,000
Vertical scale 1:2,500
Vertical exaggeration x100

Figure 3.4 Schematic hydrogeological cross-section B - B[I]

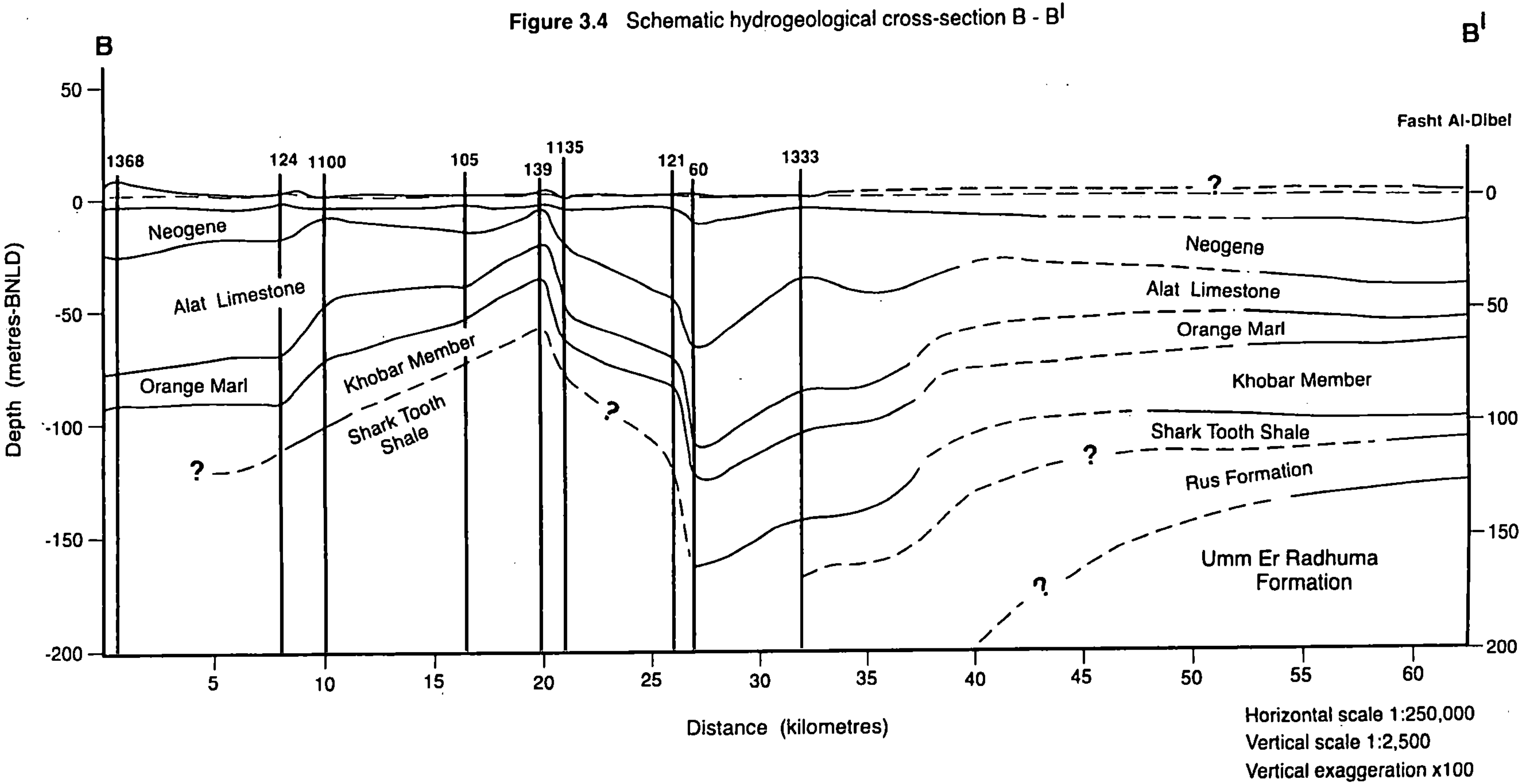
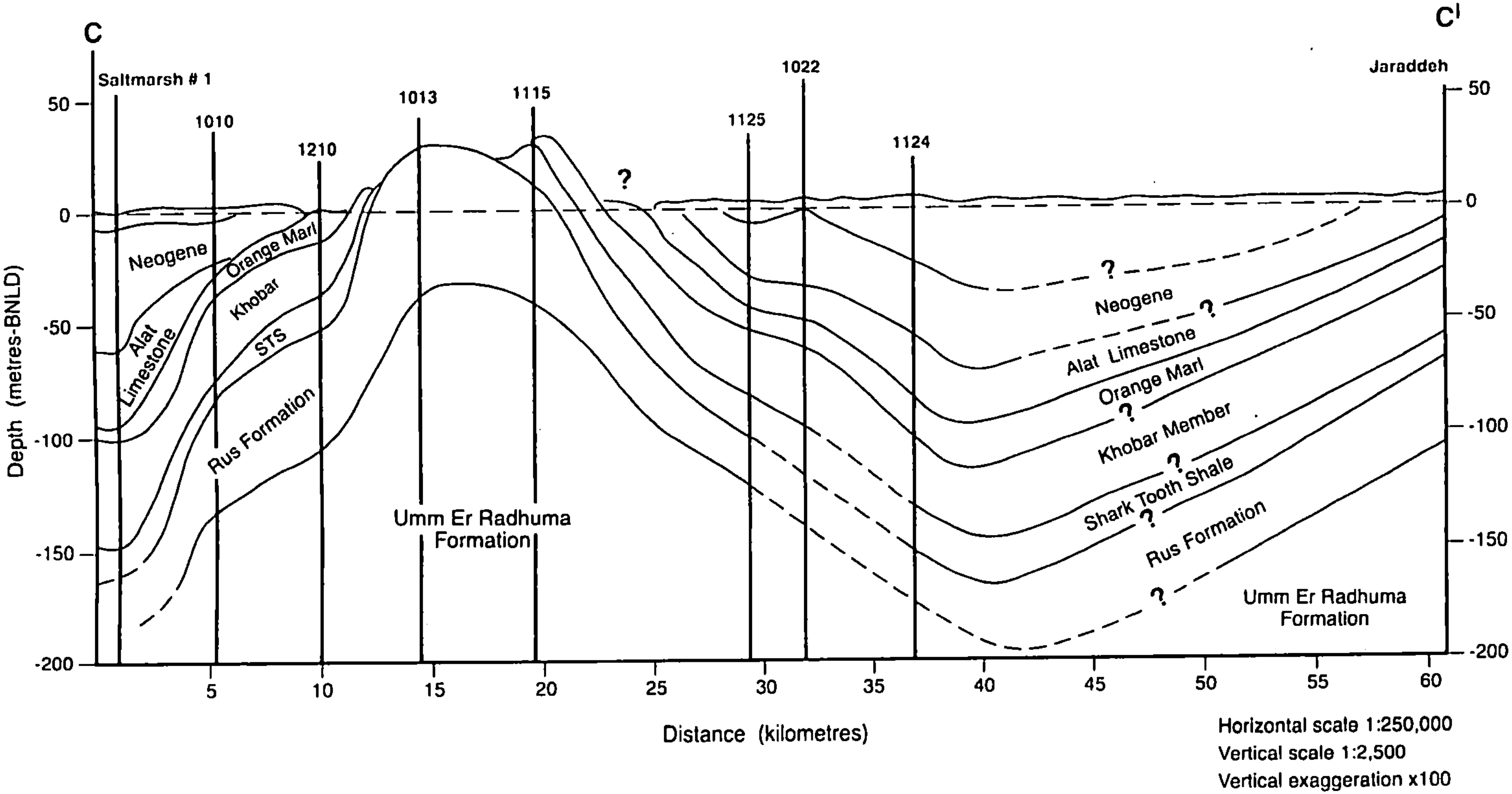


Figure 3.5 Schematic hydrogeological cross-section C - C[I]



The top of the Neogene aquifer/aquitard has been contoured as shown in Figure 3.6. The figure reveals that the Neogene occurs at depths varying from around zero to 3 m in the western and northern coasts to around 15 m in the vicinity of Hidd Town. As illustrated in Figure 3.7, the Neogene has a thickness of between 2 – 60 m, increases from the west and north to the east and northeast areas where it reaches its maximum thickness. Structural offshore drilling demonstrates significant Neogene depositional thickening in the north of Bahrain Al-Jarim offshore area. This also holds true in the case of the southern offshore area. Subsurface lithological log data suggest that the Neogene consists of calcareous claystone interfingered with, and occasionally replaced by shallow marine dolomitic limestone, with a fine-grained sandy limestone or calcareous sandstone forming the base of the sequence.

The percentage of the claystone in the Neogene sequence determines whether it behaves as an aquifer or aquitard. In the northeast of Bahrain and in Muharraq Island where the Neogene is generally thick, as can be seen in Figure 3.7, it contains a considerable amount of claystone and, hence, acts as an efficient aquitard layer confining the Alat Limestone aquifer. In the northern and western coasts, the thinner Neogene, with a claystone percentage of generally less than 30 % behaves as a very limited aquifer. Towards the offshore area between Bahrain and Saudi Arabia mainland, the Neogene reaches a thickness of about 80 m. Further west, in the coastal belt of Saudi Arabia, where the Neogene represents one of the major aquifer systems, it increases in thickness to generally more than 150 m, with domination of limestone, sandy limestone, and sandy marl facies.

Interpretation of the Alat Limestone aquifer structural contour map in Figure 3.8 indicates that the Alat is generally a shallow aquifer encountered at depths of between 5 - 50 m

Figure 3.6 Structural contour map of the top of the Neogene aquifer/aquitard

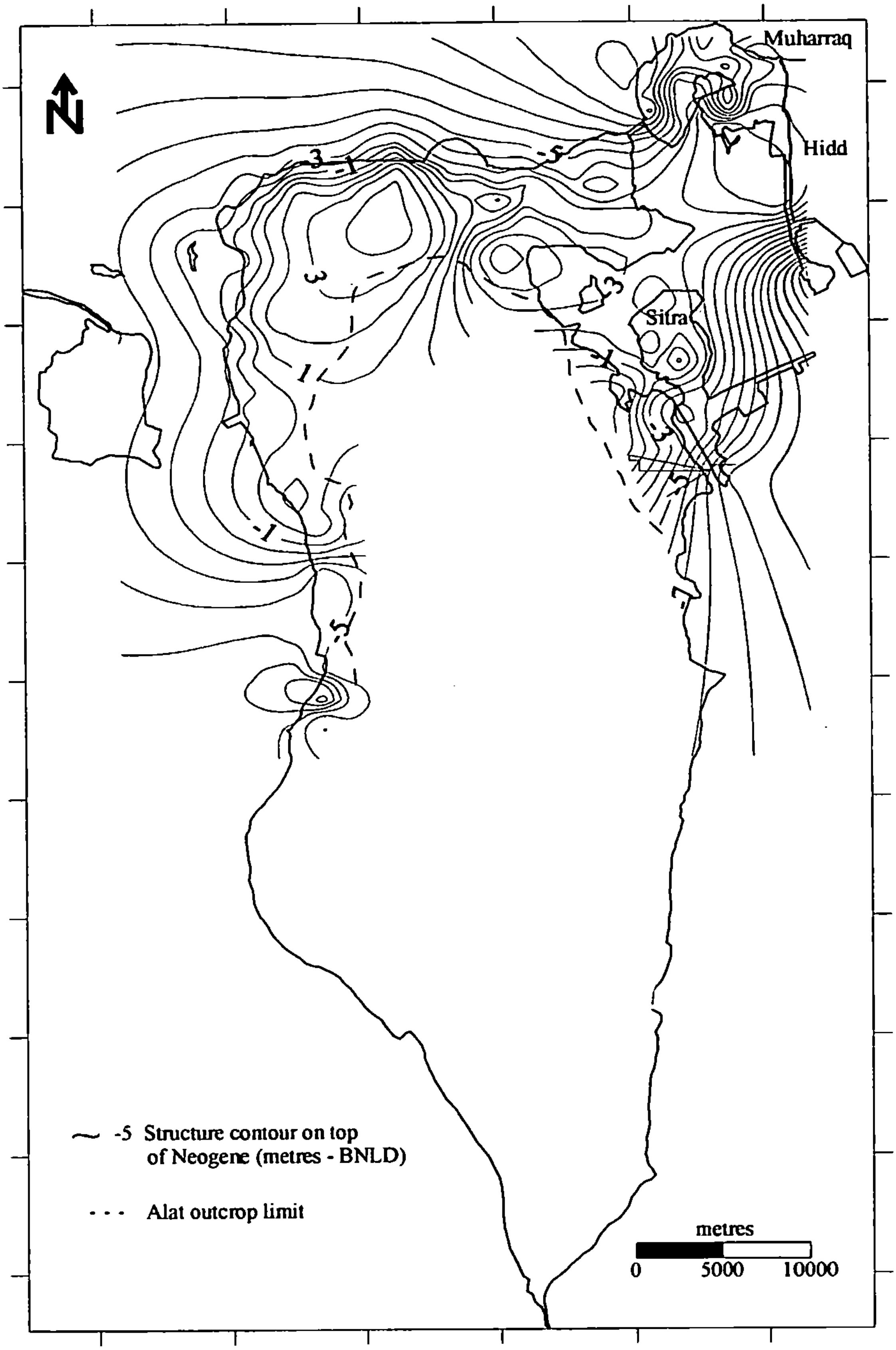


Figure 3.7 Isopachyte map of the Neogene aquifer/aquitard

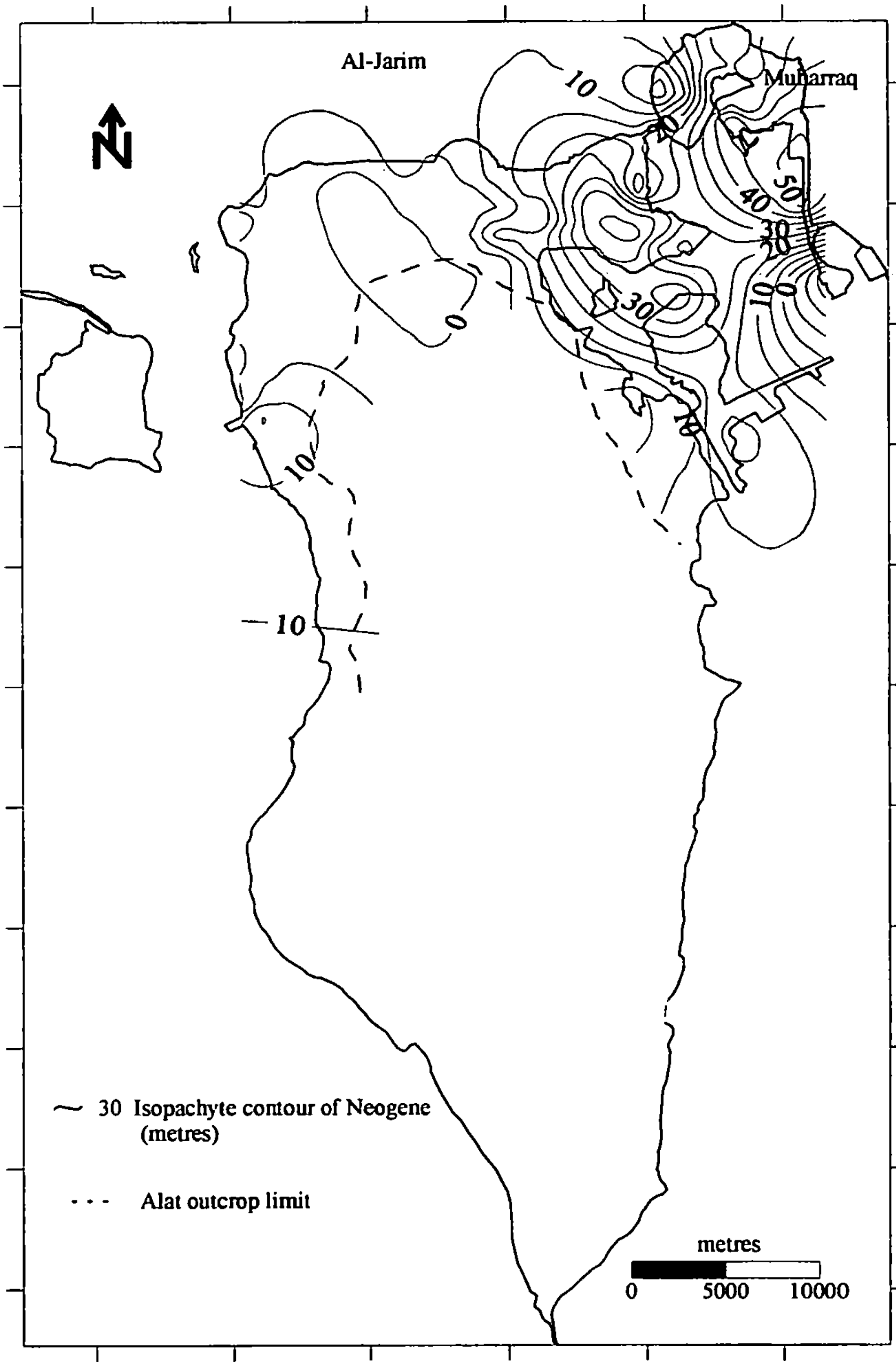
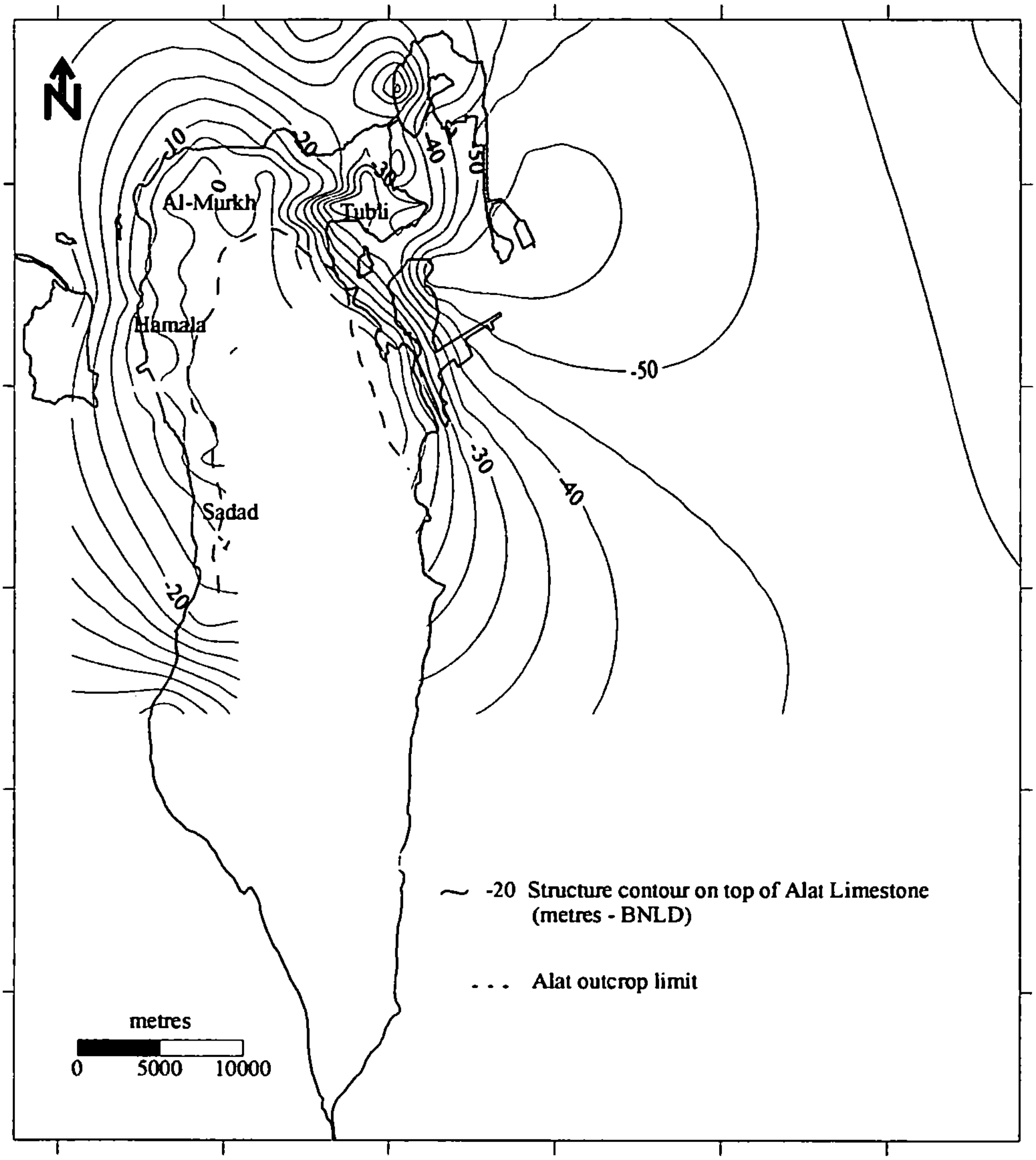


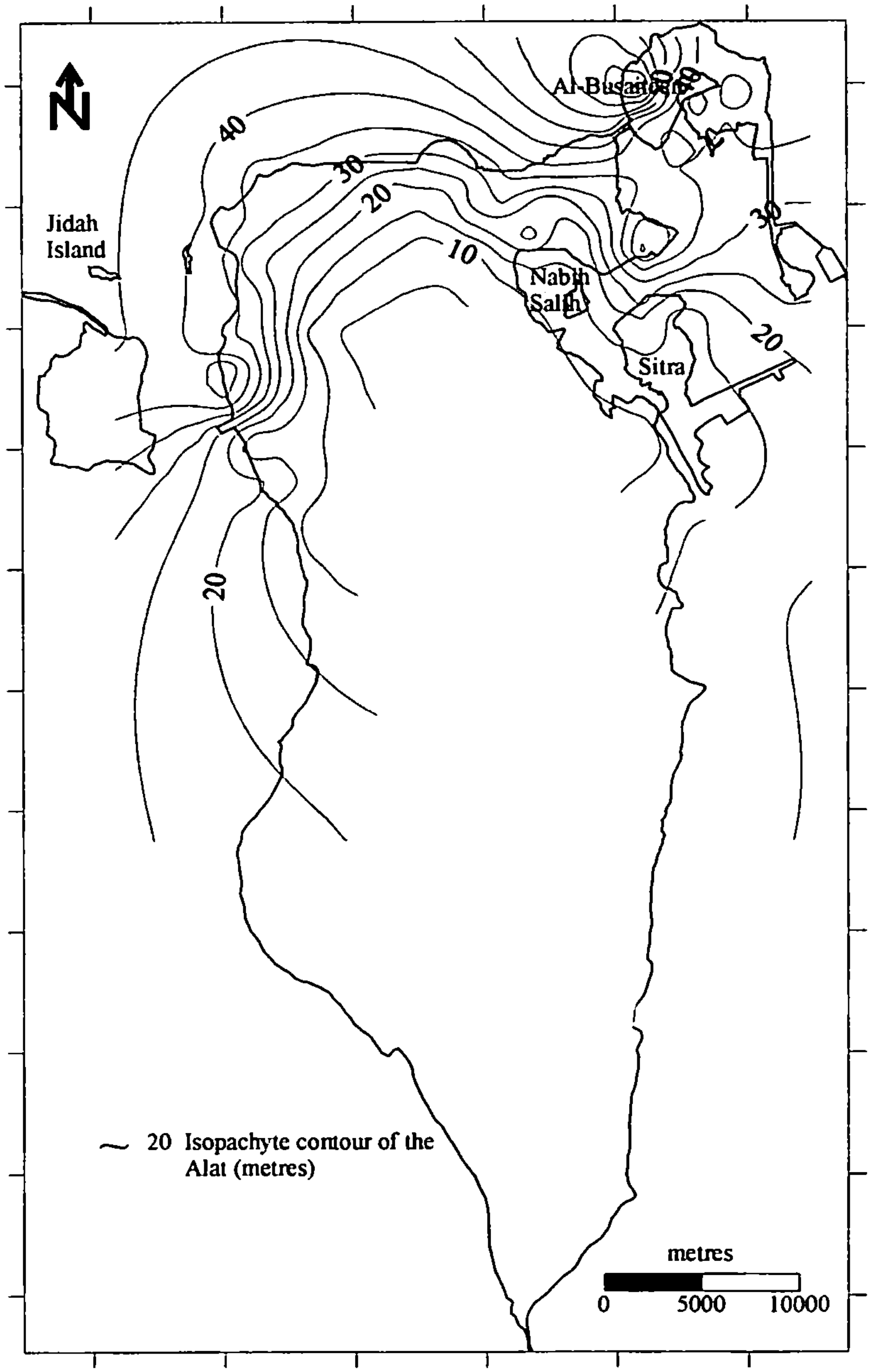
Figure 3.8 Structural contour map of the top of Alat Limestone aquifer



below the Bahrain National Level Datum (BNLD = mean sea level). This aquifer is missing in the north-central parts near Aali, and the Neogene unconformably overlies the Khobar aquifer or Orange Marl remnants. Over the crest of the anticline, the aquifer has been completely removed by erosion. Along the Hamala - Saar scarp line in the western coast, the Alat occurs under water table conditions and is virtually unsaturated. In those areas, the Neogene was completely eroded or possibly was not deposited. Surface outcrops of the Alat can also be traced northwards up to the Barbar village, passing through Janabiyah and Al-Murkh villages. In those localities, the unconfined Alat is partially saturated, rather tight, and is of generally poor yield. Further down along the western coast near Sadad and Shahrakan villages, the Alat appears absent and the Neogene unconformably overlies the Orange marl. A similar case is recognized northeastwards in the vicinity of Tubli village.

Lithological logs reveal that the Alat is made up of off-white to cream and grey, fine grained, molluscan-rich limestone and dolomitic limestone, becoming progressively off-white to light grey chalky dolomitic limestone downwards, with common casts and moulds, sporadic limonite staining, occasional ferruginous spotting, and is locally silicificified. The total Alat thickness, as shown in Figure 3.9, does not normally exceed 40 m, but localised thickening of as much as 50 m is recorded in the vicinity of Al-Busaiteen. This is probably caused by shallow structural modifications associated with the Al-Busaiteen Slumping Feature (see Figure 3.4). Elsewhere, about the eastern coast of the study area near Sitra and Nabih Salih Islands, the Alat is significantly reduced in thickness. Water well WRD 1368 in Jiddah Island, off the west coast, shows somewhat abnormal Alat depositional thickening to up to 51 m. However, it appears more likely that the interpretation of the driller's log is unreliable.

Figure 3.9 Isopachyte map of the Alat Limestone aquifer



The shape of the top of the Orange Marl aquitard is shown by the structural contours map in Figure 3.10. It indicates that the Orange Marl in the study area occurs at depths ranging from near surface adjacent to the outcrop areas to about 80 m in the northeastern coast at Qalali and Sumaheej villages. In thickness, it ranges from 9 to 15 m (Figure 3.11), but thickness abnormality is not uncommon. For instance, in a localised area around the Hamala village the Orange Marl demonstrates unusual depositional thickening to about 18 m. A minor local increase in thickness is also noticeable in the vicinity of Al-Busaiteen, which may suggest some link with the well-known solution collapse feature in that area (see Figure 3.4).

The Orange Marl aquitard at subsurface is composed of orange to pale yellow, slightly dolomitised, and commonly iron-stained marl, with frequent occurrence of marly limestone. In the western coast near Jasra and Hamala villages, the Orange Marl aquitard is dominantly represented by a light blue and dark brown shale-claystone series.

Most of the water wells drilled in the Khobar are restricted to the upper 5 to 10 m of this aquifer. This cut section is a predominantly limestone and dolomitic limestone, brown and buff, crystalline, and intensively fractured, commonly vuggy, with frequent occurrence of chert horizons, and minor secondary calcite. Occasionally, the upper few metres of the Khobar contain white and grey, often tough and fractured flint-bearing dolomite, with secondary constituents filling vugs and veins. In a few places, notably about the eastern sides of Dar Kulaib and Malchiyah villages, this highly transmissive part of the Khobar aquifer is not present, and appears to be replaced by pure white, fine-grained, flaky and non-fractured limestone, resulting in relatively poorer aquifer yield. Geophysical and drillers' logs from fully penetrating boreholes indicate that the rest of the

Figure 3.10 Structural contours map on top of the Orange Marl aquitard

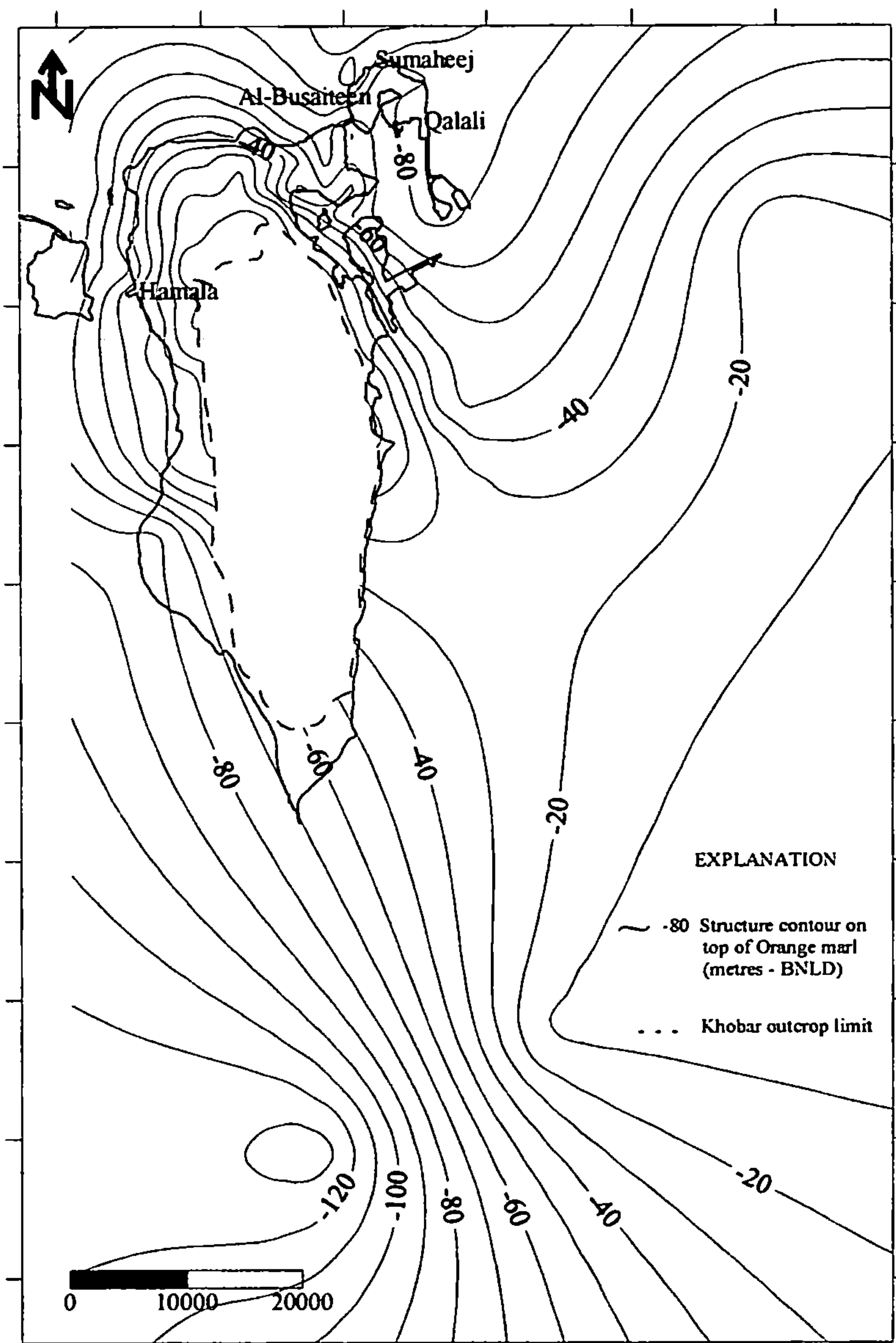
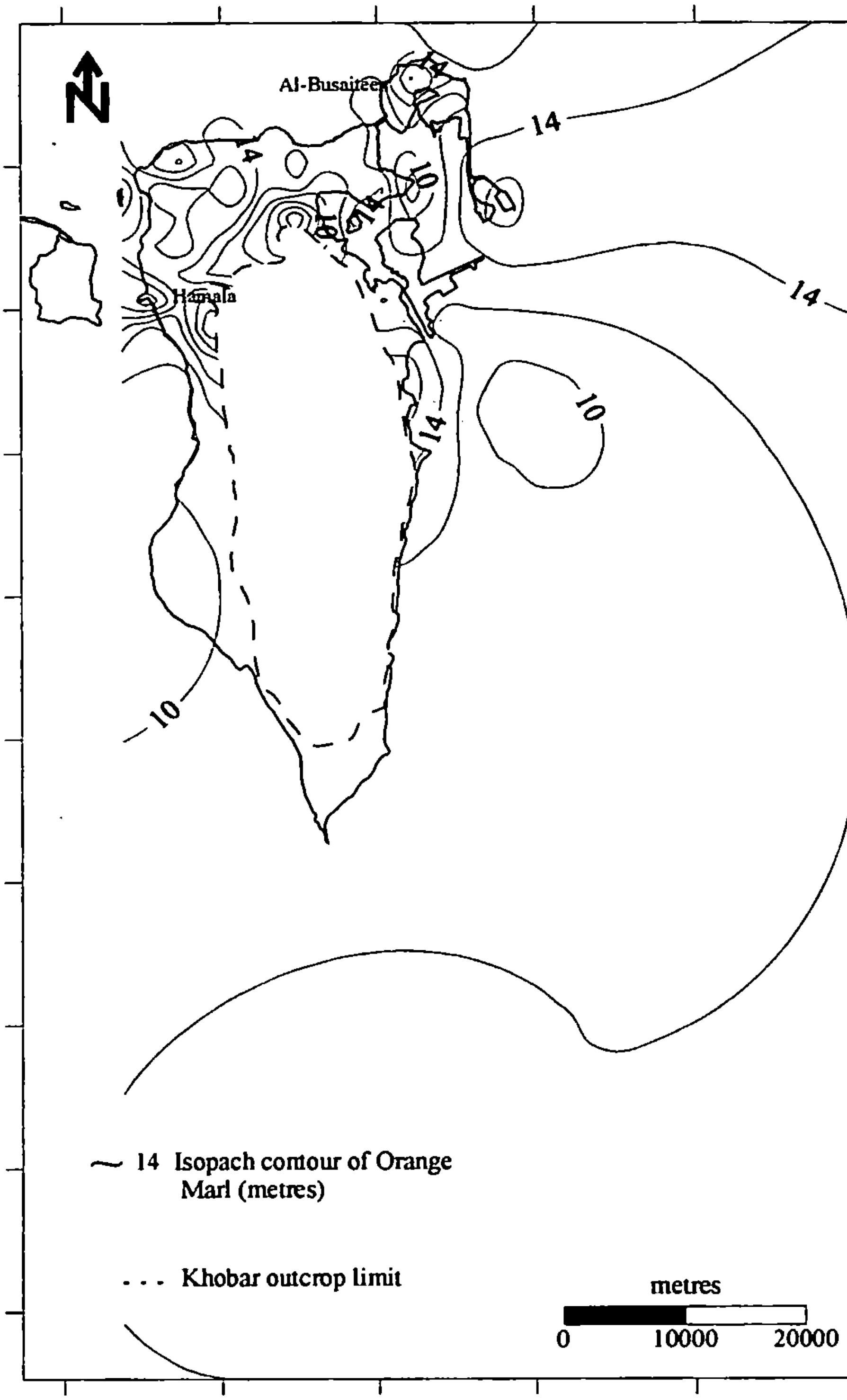


Figure 3.11 Isopachyte map of the Orange Marl aquitard



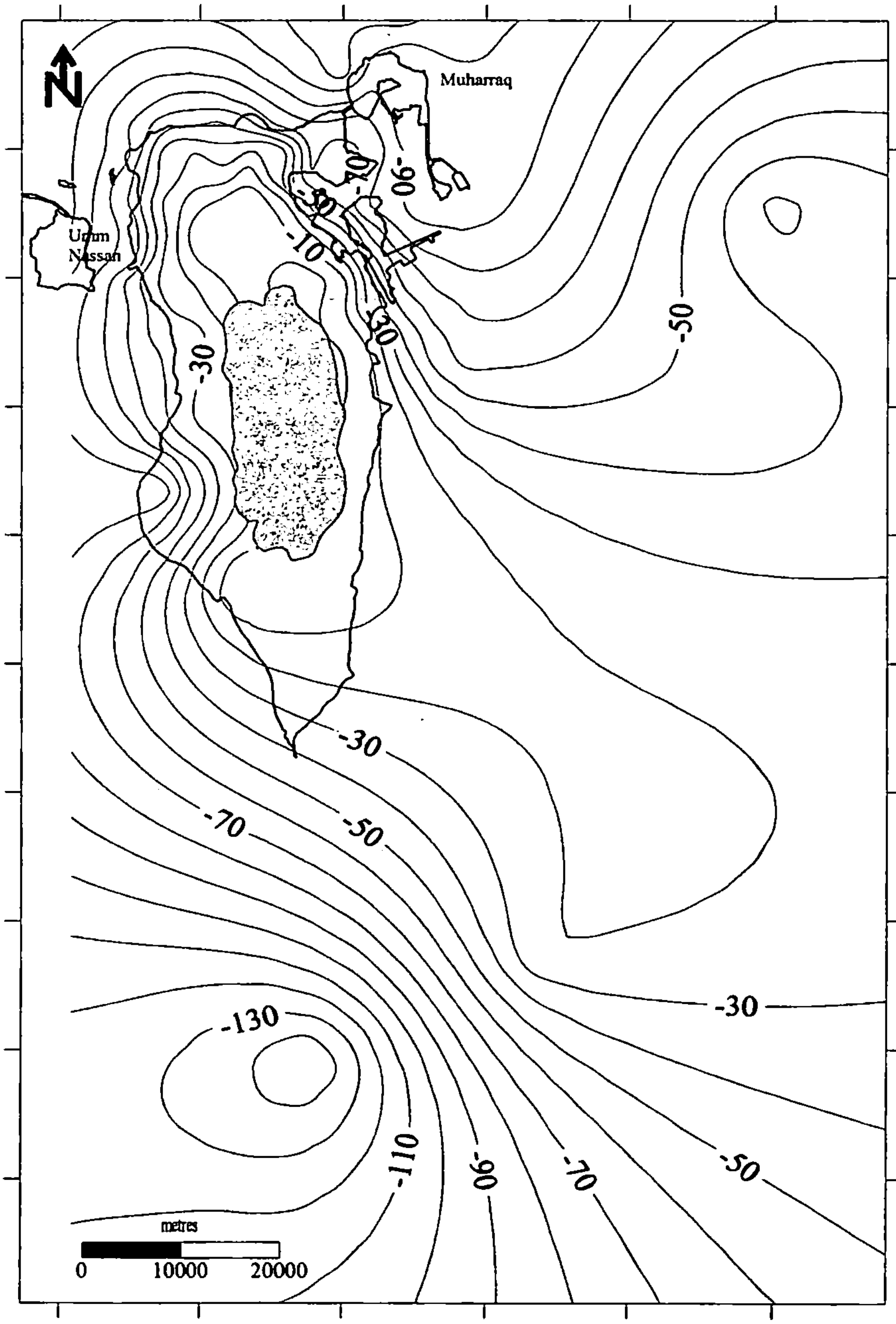
sequence is chiefly light brown, friable and saccharoidal dolarenite/calcarenite facies, and off-white to pinkish brown, loosely cemented, *Nummulites*-bearing limestone (*Alveolina* limestone), with some marly limestone interbeds, and a distinctive basal marl.

Apparently, the map showing the depth to the surface of the Khobar aquifer (Figure 3.12) reflects the general eastward and westward dipping of the Bahrain dome, with depths to the aquifer increasing away from the centre of the dome. It is encountered at depths ranging from about 5 m in southeastern coast near the outcrop area to about 90 m in Muharraq and Umm Nassan Islands. Towards the eastern and southeastern Bahrain offshore areas, the aquifer becomes gradually shallower. The depth to the top of Khobar is, however, increases to between 110 – 130 m at the northern offshore area. In most cases where the Khobar is extensively developed, it is found under artesian conditions, but it is unconfined in the north central, south central, and southeastern parts of the main island. The unconfined Khobar in the south central areas is completely dry, whereas it is partially saturated around the southeastern parts.

The isopachyte map of the Khobar aquifer is illustrated by Figure 3.13. The map shows that this aquifer is completely eroded over the crest of the Bahrain Dome, crops out near the eroded edges around the dome, and thickens considerably in the structural lows. It ranges in thickness from less than 6 m in the southeastern coast to over 40 m about the northeastern and southwestern coasts near Al-Jazair.

Evidence from borehole logs indicates that the Shark Tooth Shale aquitard is predominantly a grey-green and blue-grey, sub-fissile, often non-calcareous and pyritic claystone-shale series, with sporadic buff and grey, slightly shaly calcian dolomite, with

Figure 3.12 Structural contour map of the top of the Khobar aquifer

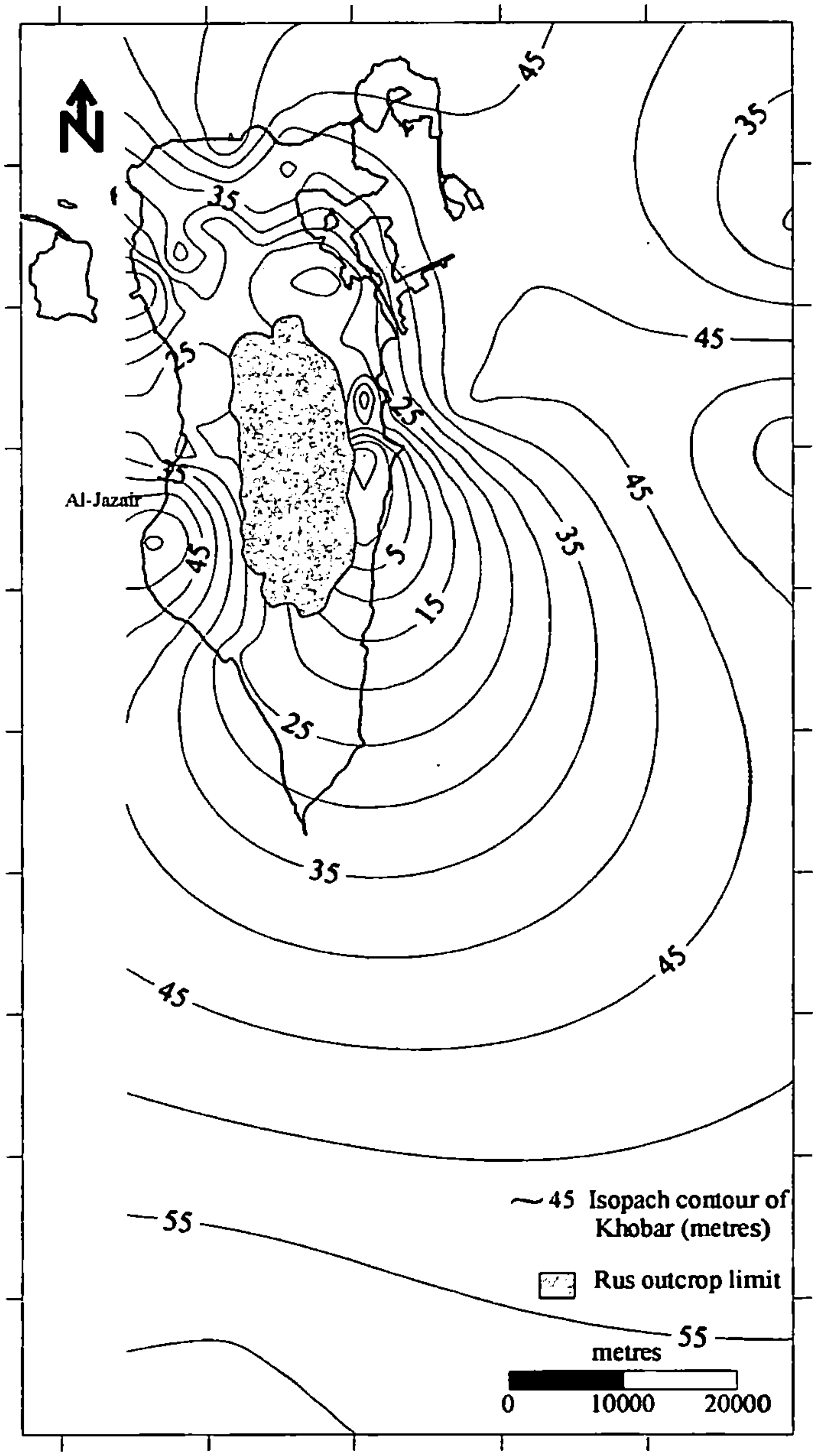


EXPLANATION

-60 Structure contour on top of khobar (metres - BNLD)

Rus outcrop limit

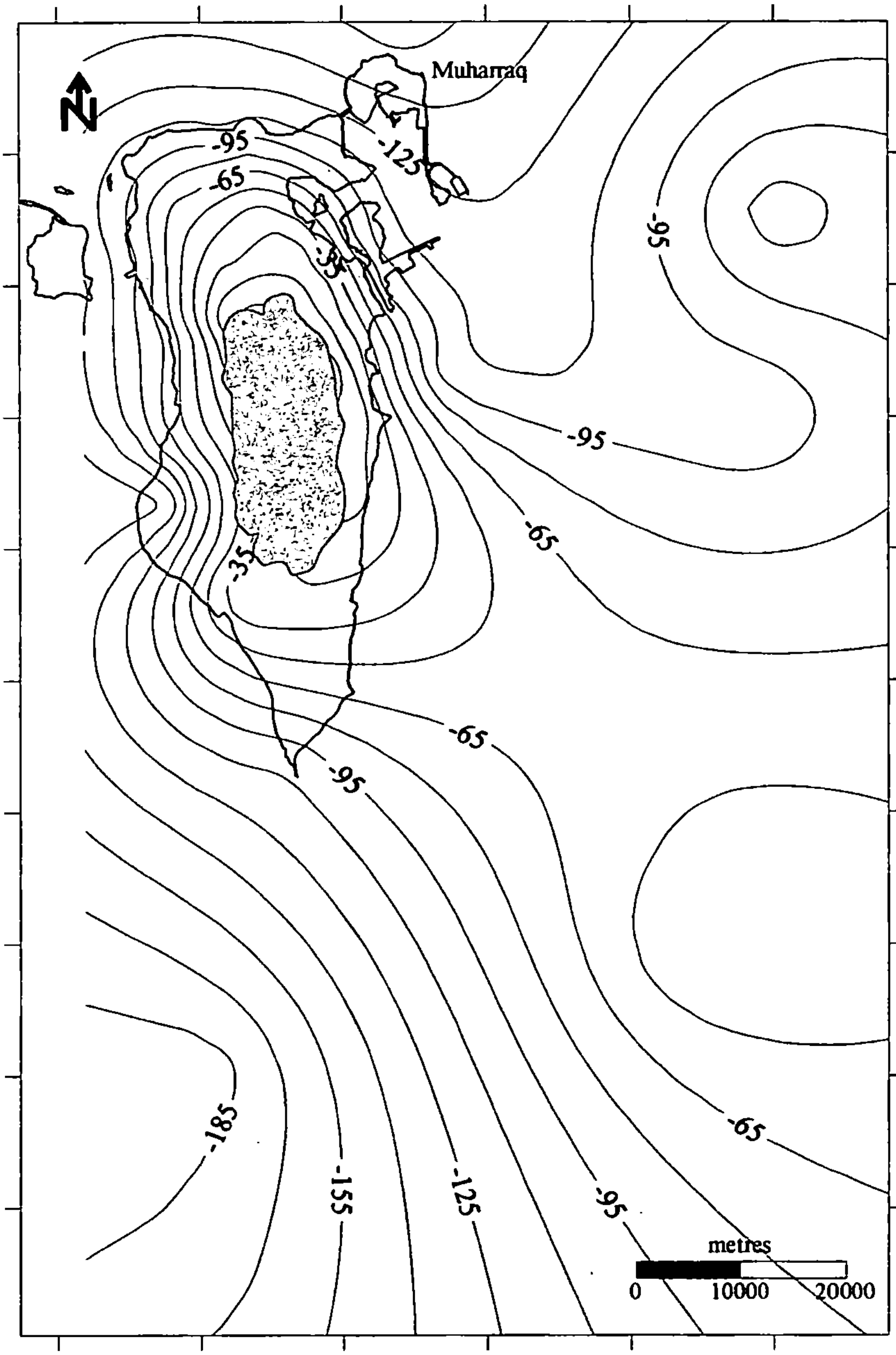
Figure 3.13 Isopachyte map of the Khobar aquifer



frequent dark brown lignitic shale. The depths to the Shark Tooth Shale vary from about 5 m near the southeastern edge of the rim rock to about 135 m in the northeastern areas, more specifically around Muharraq Island. This is shown by the structure contours map in Figure 3.14. Figure 3.15 illustrates the isopachytes of the Shark Tooth Shale; it shows that this aquitard is normally between 8 – 20 m thick. It thins out near the crest of the dome to about 2 m, whilst the eastern and southwestern areas demonstrate depositional thickening to up to 19 m. The Shark Tooth Shale appears to have been substantially reduced in thickness at the southern and northern plunges, whilst it exhibits depositional thickening towards the western flank between Bahrain and the Saudi Arabia mainland.

The Rus Formation in the study area is composed primarily of cream to brown and olive green, chalky dolomite, dolomitic limestone, and calcarenitic limestone, often interbeded with marls, with abundant quartz geode horizons. The Rus sequence also contains variable amounts of blue-grey and cream, gypsiferous shale/claystone; bluish-grey, massive anhydrite; and spary to light grey gypsum. The maps in Figures 3.16 and 3.17 show the structural configuration and thickness distribution of the Rus aquifer/aquitard, respectively. Figure 3.16 indicates that the Rus in the study area can be reached at depths between zero in the structural highs where it crops out, to more than 140 m off the dome structure. Its thickness ranges from slightly less than 60 m to over than 145 m (Figure 3.17). The Rus attains a thickness of about 60 m near the core area; but thickens considerably to about 150 m in the synclinal region between the Bahrain anticline and Dammam Dome. In addition to depositional differences possibly attributable to the synsedimentary growth and Post-Dammam erosional phase, the reduction in the Rus thickness on the crest of Bahrain anticline can be partially explained by removal of evaporites by solution as evident from lithological logs and surface collapse structures.

Figure 3.14 Structural contour map of the top of the Shark Tooth Shale aquitard



EXPLANATION

-95 Structure contour on top of Shark Tooth Shale (metres - BNLD)

Rus outcrop limit

Figure 3.15 Isopachyte map of the Shark Tooth Shale aquitard

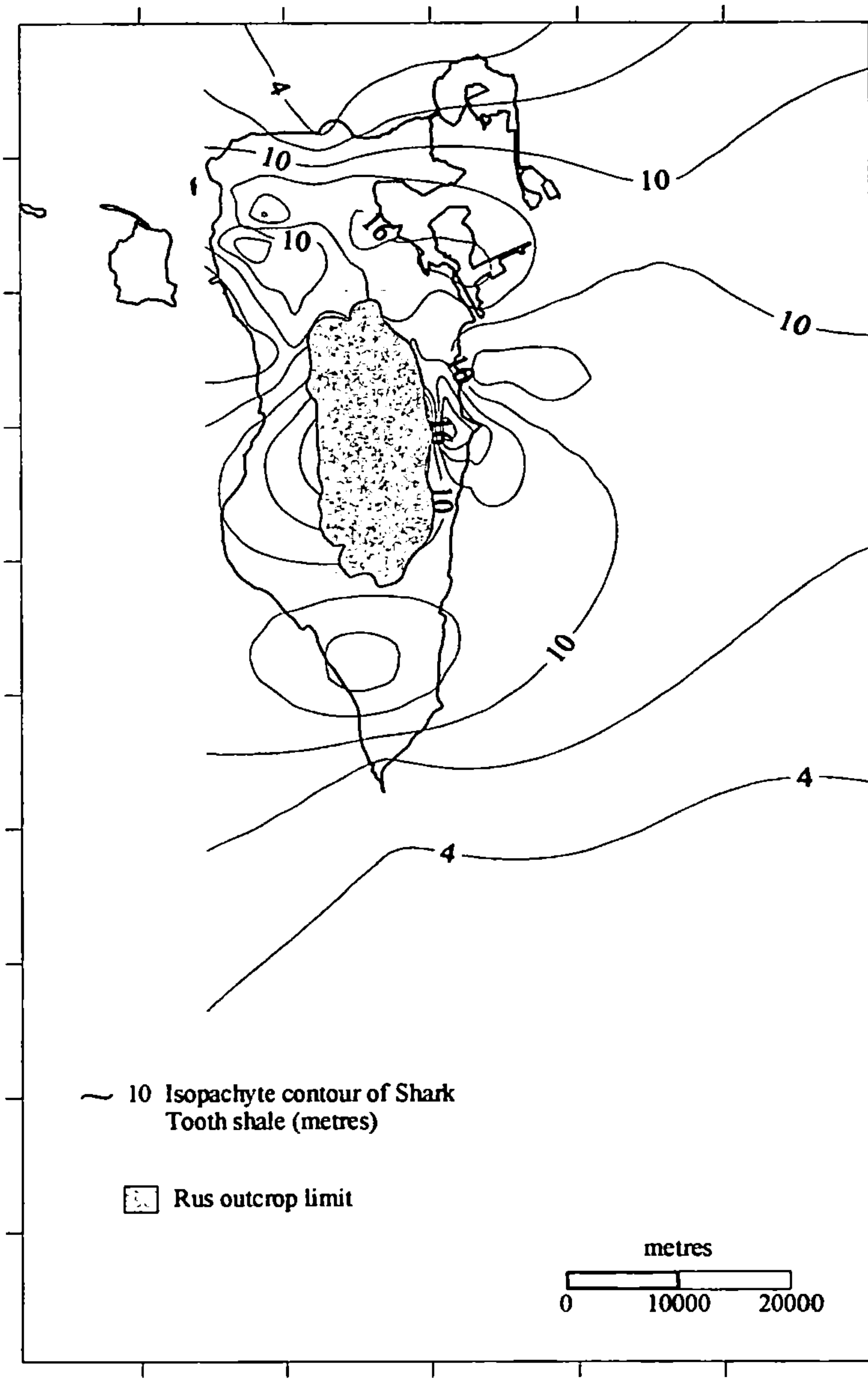


Figure 3.16 Structural contour map of the top of the Rus aquifer/aquitard

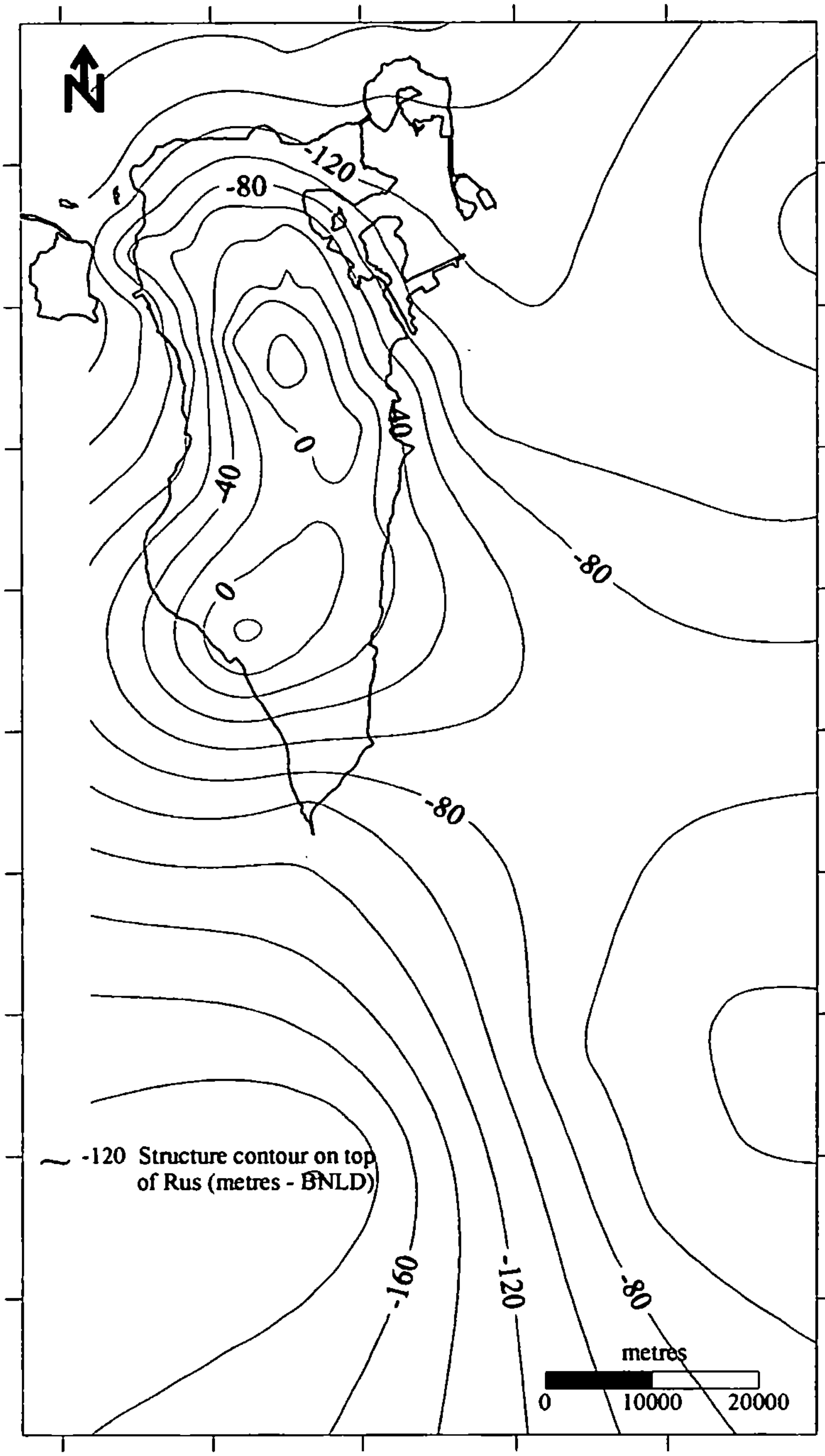
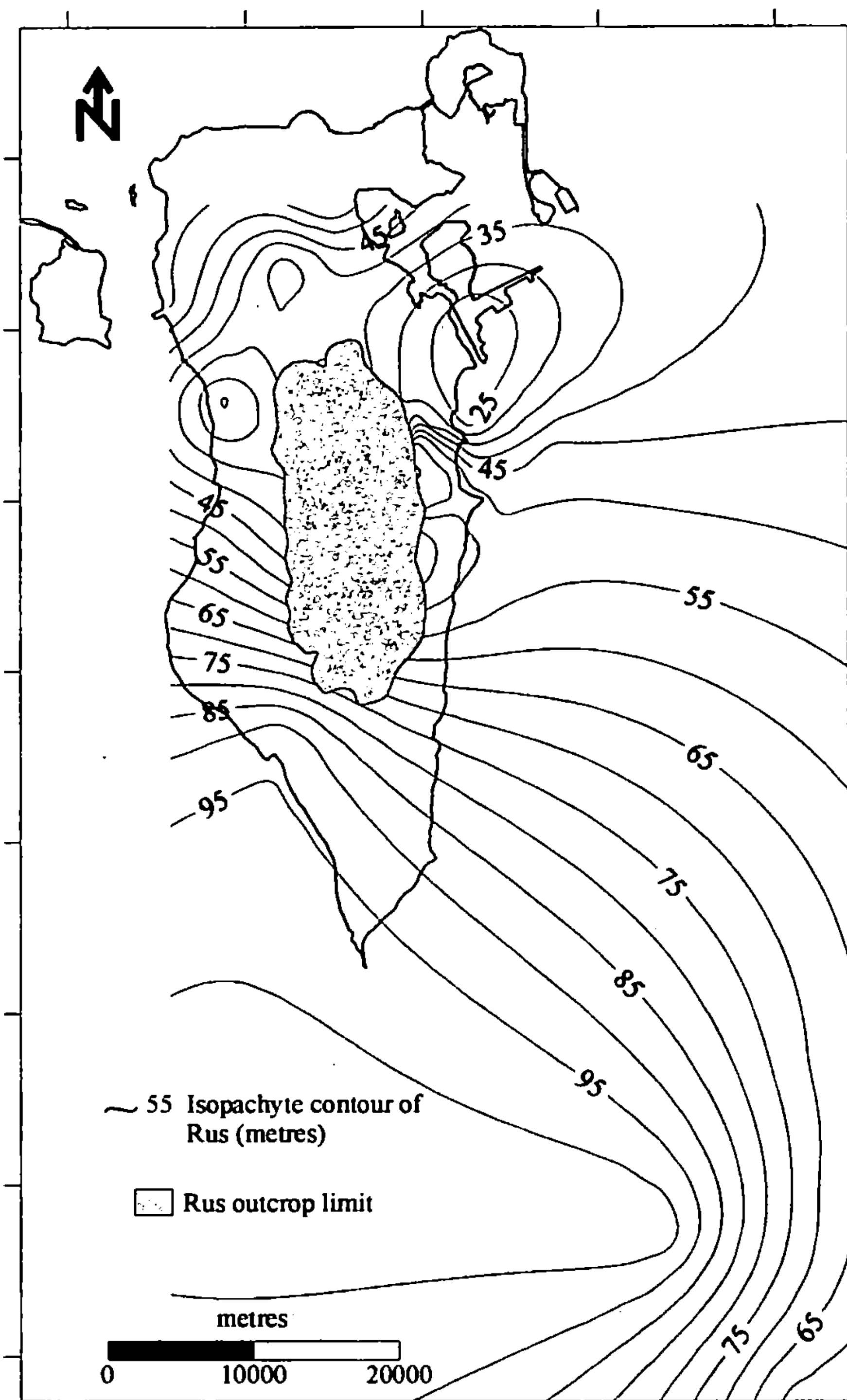


Figure 3.17 Isopachyte map of the Rus aquifer/aquitard

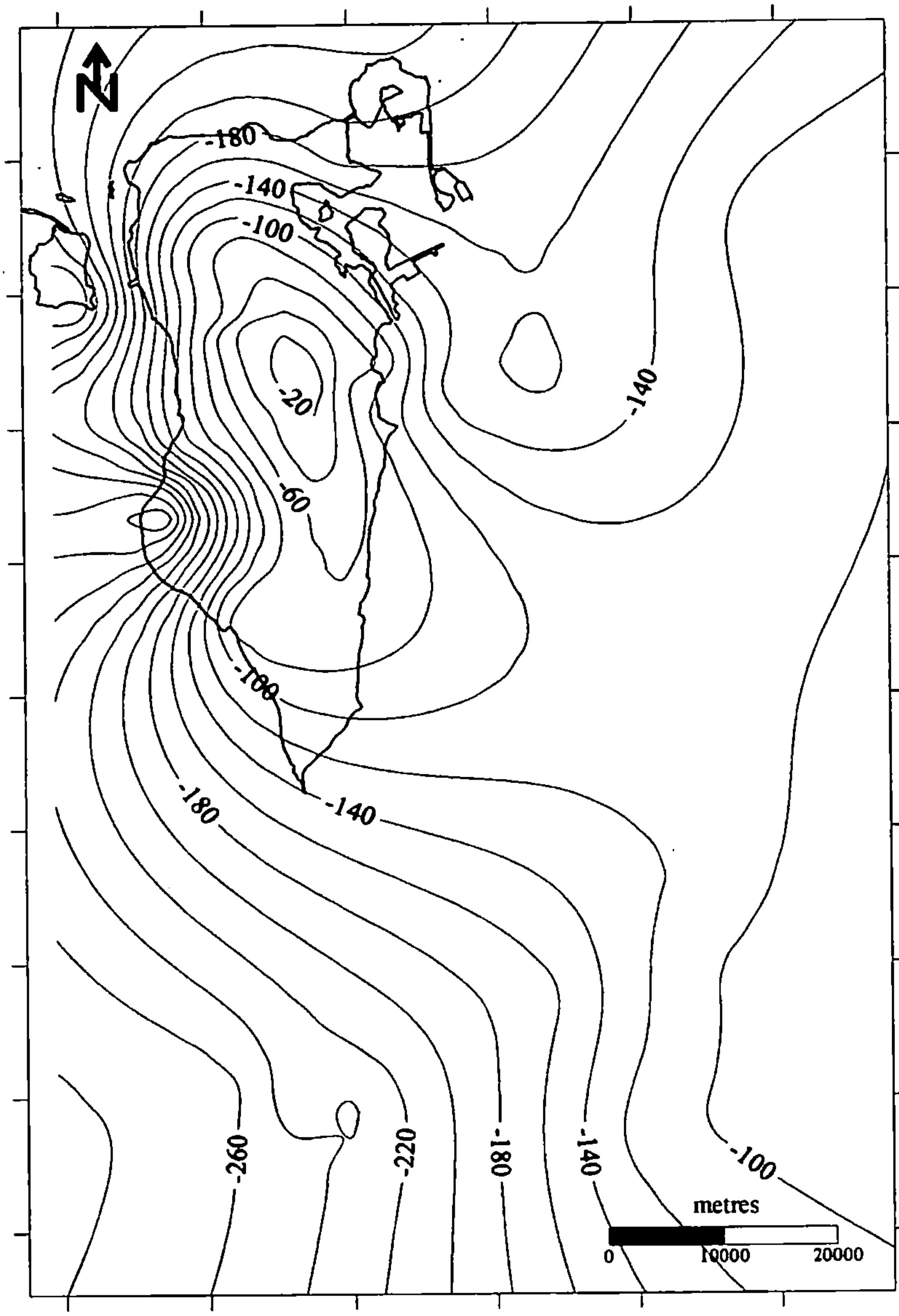


At that part of the island, the unconfined Rus is partially saturated, and is believed to be in hydraulic continuity with the Umm Er Radhuma aquifer. On most of the structural lows, notably on the western flank and northern plunge of Bahrain Dome, the Rus increases in thickness with appreciable percentage aggregate of evaporites and shale (GDC, 1980b). This could mean that the Rus in those areas is functioning as an efficient aquitard confining the Upper Umm Er Radhuma aquifer, and, together with the Shark Tooth Shale, separating the Dammam aquifer system from the Rus - Umm Er Radhuma aquifer system. Quoting GDC (1980b), in the eastern flank, major evaporite leaching has taken place, resulting in the non-anhydritic Rus acting as an aquifer linked hydraulically with the Umm Er Radhuma aquifer.

Lithologically, the Umm Er Radhuma is a grey to olive green and sometimes buff, friable, vuggy and often foraminiferal dolomitic limestone, with subordinate calcian dolomite and calcarenite facies, becoming increasingly argillaceous towards the stratigraphic boundary with the Aruma Formation. Contours on the surface of the Umm Er Radhuma (Figure 3.18) clearly show that this formation is not present at surface. The depth to the Umm Er Radhuma gradually increases from about 30 m just beyond the crest of the Bahrain dome to more than 260 m in the western synclinal area, and to about 140 m towards the eastern synclinal area. The thickness of this formation, as displayed in Figure 3.19, ranges from a minimum of about 140 m at the crest of Bahrain anticline to greater than 300 m in the off-dome structures. Such an off-structure thickening reaches about 280 m in the eastern flank, and nearly 240 m in the western flank of the dome.

Only a few water wells penetrate the Aruma aquitard; most of them only tap the upper part of the formation. Examination of the lithologic logs of these wells indicates that the

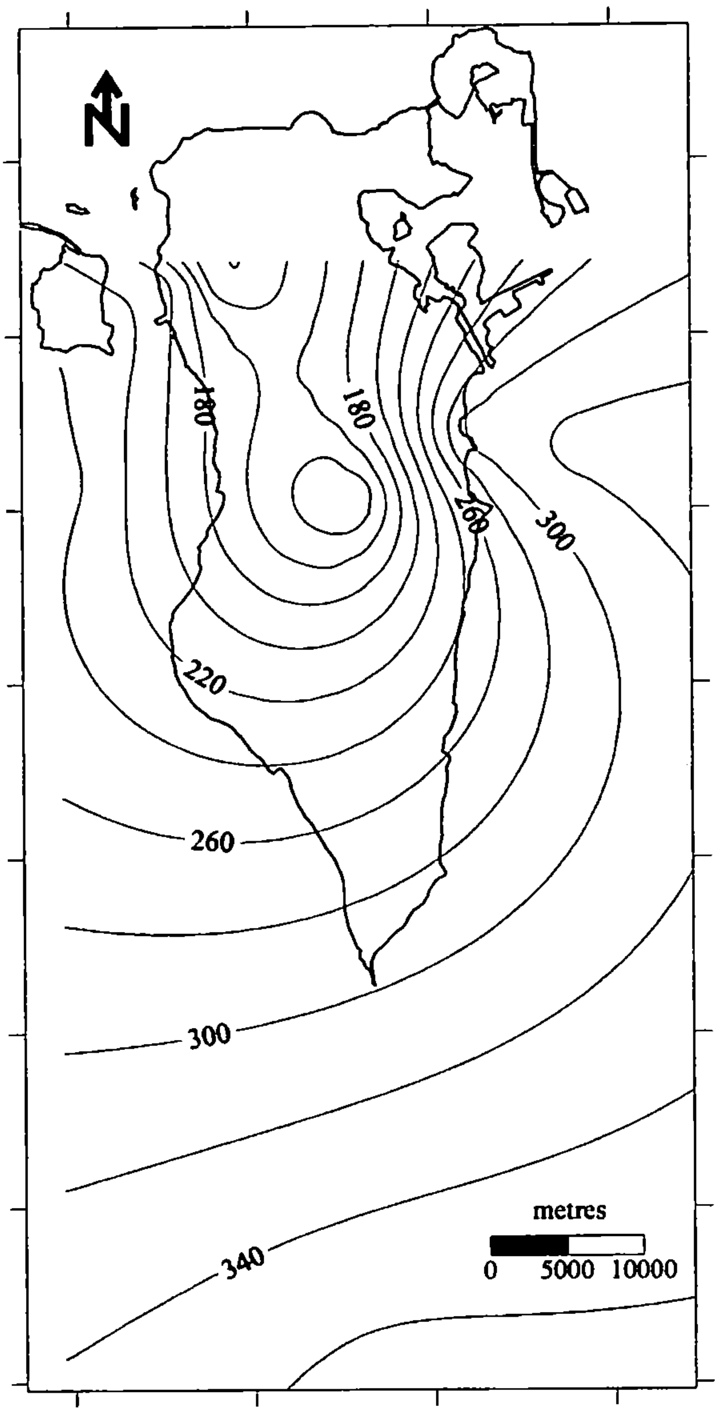
Figure 3.18 Structural contour map of the top of the Umm Er Radhuma aquifer



EXPLANATION

-140 Structure contour on top of Umm Er Radhuma (metres - BNLD)

Figure 3.19 Isopachyte map of the Umm Er Radhuma aquifer



EXPLANATION

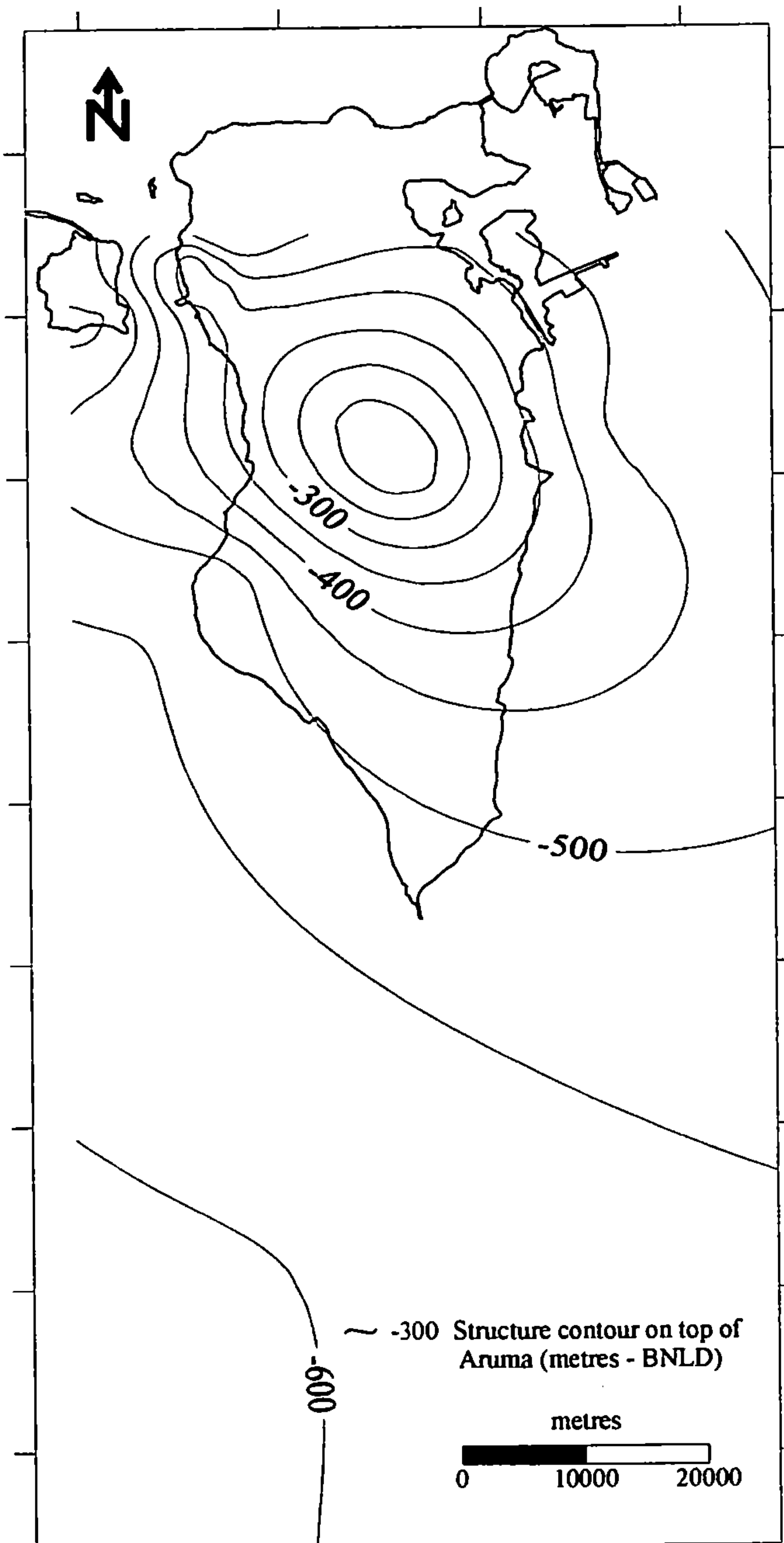
220 Isopachyte contour of the Umm Er Radhuma (metres)

Aruma comprises dark brown and dark grey shale, interbeded with dark grey dolomitic limestone, becoming argillaceous downwards, with off white and greyish cream argillaceous limestone occurring sporadically throughout the formation. A structure contour map of the Aruma surface is shown by Figure 3.20. The upper boundary of the Aruma lies at depths from about 300 m near the crest of Bahrain Dome, increases to about 500 m towards the marginal areas. The Aruma thickness has been shown by BAPCO exploratory drilling to be as much as 260 m at the crest of the dome, thickening to about 310 and 275 m under the western and eastern flanks, respectively. These records also show the Aruma attaining a thickness of around 520 m in the northern coast, and gradually increasing to around 550 m in the northern Bahrain Al-Jarim offshore area. Close to the coastal zones of Saudi Arabia mainland, the Aruma reaches a thickness of between 400 – 600 m (Bakiewicz *et al.*, 1982).

3.4 Aquifer and Aquitard Hydraulic Properties

The Tertiary carbonate rocks that form the aquifer units in Bahrain possess two types of porosity: a primary porosity developed among rock grains and fabric during the time of deposition, and the secondary porosity which developed along karsitic fractures, and solution enlarged joints and veins. Secondary porosity is also developed in fossil mould and cast spaces, from which the original shell material has been removed, and as formation of void spaces consequent on dolomitisation (GDC, 1980b). The development and distribution of the aquifer hydraulic properties, particularly the evolution of the secondary porosity is controlled by the main domal structure, and the minor structural features along the Dammam dip slope. In general, secondary type porosity increases in the structurally high areas along the crest of the dome, and at the upper parts of the aquifer

Figure 3.20 Structural contour map of the top of the Aruma aquitard



units, whilst it is much lower in the off-the-dome synclinal areas where primary porosity appears to dominate.

3.4.1 The Dammam Aquifer System

The Dammam Aquifer System, as already demonstrated, is a composite system comprising two aquifer units: the Alat Limestone and Khobar aquifers. The Alat Limestone aquifer porosity is mainly developed between the intergranular spaces, and as a result of dissolution of Molluscan shells. Vertical variation in the Alat permeability with depth is not common, although minor facies changes to chalky and less fossiliferous dolomitic limestone do occur as the base of the aquifer is approached. Information from neutron porosity geophysical logging carried out by GDC strongly supports this conclusion. Estimates of mean permeability for the Khobar full section are limited because of the normal drilling practice of partial penetration. Therefore, most of the available estimates are cut section permeabilities. This constraint is less evident in the case of the commonly fully penetrated Alat wells.

The upper part of the Khobar is a normally compact, but intensively karstified dolomite and dolomitic limestone. Caliper logs indicate a high incidence of fissures in this part, often associated with extreme variation in neutron log porosity. Core samples examined by GDC (1980b) show that the permeability of the rock matrix of this section is very low. Further, drilling operations reveal that the uppermost part of the Khobar normally coincides with a total loss of circulation fluid, implying major fracturing and active fissure flow at this zone. Fracturing frequently extends up to the base of the Orange Marl aquitard resulting in occasional circulation losses at this horizon before reaching the top of the Khobar. Significant local variation in the upper Khobar transmissivity is common even within short distances, as wells located near one another can have large differences in yield. This may be indicative of variable fracturing intensity, but it might also be due to plugging of karsitic features by secondary constituents. Below this highly transmissive zone, which has a maximum thickness of about 10 m, the Khobar is a friable dolarenite and granular Alveolina limestone, with mainly intrinsic porosity, suggesting that the Khobar aquifer exhibits pronounced lateral permeability variation with depth.

Little information is available on the hydraulic properties of the Alat Limestone in the study area. Wright (1967) failed to perform tests on wells tapping this aquifer using constant head/ variable discharge method because of head variation with tidal loading. Instead, he reported hydraulic properties for the Alat from the analysis of unsteady state pumping tests performed for wells in the coastal belt of Saudi Arabia mainland by Layne and Dimmock (1955). The range of transmissivities derived from these tests was from 136 m^2 day^{-1} to 448 m^2 day^{-1}. This suggests permeabilities in the range of 4 to 13 m day^{-1}, assuming a normal Alat penetration of 35 m. Storage coefficient estimates were in the range of $1.3 \times 10^{-4} - 5.3 \times 10^{-4}$ (Layne and Dimmock, 1955 cited in Wright, 1967), indicating confined conditions.

The Alat Limestone aquifer transmissivity in the coastal belt is also reported to range from 150 to 240 m^2 day^{-1} (Italconsult, 1971). Abdurrahman and Rasheeduddin (1994) stated that around the Dammam Dome the average transmissivity of the Alat aquifer varies from 27 m^2 day^{-1} to 199 m^2 day^{-1}, with the average being 113 m^2 day^{-1}. They reported storage coefficient values ranging from 1.5×10^{-4} to 2.6×10^{-4}, again suggesting confined behaviour.

BAPCO keeps records for some 185 specific capacity tests, of which 25 tests are for the Alat aquifer. These data were statistically analysed by GDC in 1979 during the Umm Er Radhuma Study, and gave a mean permeability value of 14 m day^{-1}, assuming an Alat thickness of 25 m. On average, this is almost an order of magnitude higher than the value obtained for the Saudi Arabia coastal belt. A very approximate estimate, based on the specific capacity tests, puts the average transmissivity of the Alat at about 350 m^2 day^{-1} (GDC, 1980b), which is also considerably higher than the mean values calculated for the aquifer in the mainland.

A considerable amount of pumping test data has been amassed for the Khobar aquifer as a result of a numerous studies and investigations. Tidal loading shows daily maximum fluctuations of between 0.4 and 0.8 m, and the combination of very high transmissivity and very low storage in the confined fractured Khobar leads to extremely rapid attainment of steady state, with apparent absence of transient drawdowns (GDC, 1980b). The last assertion is also applicable to the fissured Umm Er Radhuma aquifer, and is responsible for the lack of information on storage properties for both aquifers.

BAPCO have carried out a number of pumping tests at three major pumping centres. Data were analysed using the steady-state method that yielded an average permeability value of 161m day^{-1}. Assuming an average Khobar thickness of 30 m, Wright (1967) calculated a mean transmissivity value for this aquifer of about 4,907m^2 day^{-1}. Wright conducted three pumping tests himself, of which only one involved unsteady-state analysis. The data were analysed using a modification of the Thiem method for steady-state conditions and the Jacob straight-line method for unsteady-state. Transmissivities of between 1,242 and 6,211 m^2 day^{-1} were calculated, and a storage coefficient value of 4.77×10^{-4} was obtained for the unsteady-state test. Selected hydraulic properties of the Dammam aquifer system reported by the early investigations are given in Table 3.1.

The BAPCO specific capacity records include 55 tests for Khobar-only completion and 31 tests for Alat-Khobar combined completion. From these data, transmissivities were calculated using Logan's equilibrium approximation method, with no allowance for well losses, implying unreliable results (GDC, 1979). Permeability values for the Khobar-only completion and dual completion wells were estimated by dividing the transmissivity by the penetrated thickness of the aquifer. This produces permeability estimates of about 306 and 321 m day^{-1} for the Khobar only and dual penetration, respectively, which clearly indicates that in the case of Alat-Khobar dual completion wells, most of the production is from the Khobar (GDC, 1980b). A mean permeability value of 80 m day^{-1} is calculated for the Khobar full section.

In 1979, GDC undertook an extensive pumping test campaign as part of the Bahrain Assignment of Umm Er Radhuma Study. This campaign included testing of 24 wells drilled into the Khobar and Rus - Umm Er Radhuma aquifers. In the case of the Khobar aquifer, credible transmissivity estimates were obtained from the step-drawdown tests, applying various approximation methods. The results have shown that the Khobar transmissivity is extremely variable, ranging from a minimum of 47 m^2 day^{-1} to a maximum of 41,280 m^2 day^{-1}, which clearly reflects the high degree of heterogeneity of the Khobar. The lowest transmissivity is reported from the pumping test of well BT21K located along the Saar-Hamala scarp, and, according to GDC (1980b), is possibly associated with the sub-surface dislocation along the scarp line caused by dissolution of the Rus anhydrite and possible shallow faulting. Analysis of pumping test data of well

Table 3.1 Selected transmission and storage properties of the Khobar aquifer (after the early investigators)

Well no.	Location	Transmissivity ($m^2\ day^{-1}$)	Permeability ($m\ day^{-1}$)	Storage coefficient (dimensionless)	Test performed by and year	Remarks
28/29[1]	Budaiya	5700	199[2]	---	BAPCO (1952)	Steady State analysis
15/2	Zallaq	5670	186	---	BAPCO (1952)	Steady state analysis
2/1	Manama	3930	129	---	BAPCO (1952)	Steady state analysis
73/318[1]	Wasmiyah	6230	200	---	Wright (1967)	Steady state analysis
---	Isa Town	1240	51	4.8×10^{-4}	Wright (1967)	Transient analysis
550	Hamala	1610	---	---	Wright (1967)	Transient analysis

[1] Two wells pumped and observed alternatively. Results represent average of two values.
[2] Estimated based on Khobar average cut section of 30m.

BS20K situated approximately 120 m down the scarp produced a transmissivity value of 19,750 m^2 day^{-1}, confirming that the former transmissivity value is an exception caused by some structural modifications.

Thus, Khobar permeability values have a huge range from a minimum of 1.4 m day^{-1} to a maximum of 2,500 m day^{-1}. Only two storage coefficient estimates were derived using the tidal efficiency method. Storage coefficient values obtained were 5.1×10^{-5} and 8.8×10^{-5}, indicating a confining character. Table 3.2 gives some selected values of hydraulic characteristics for the Khobar aquifer obtained from the 1979 pumping test programme.

In 1983, GDC investigated the hydraulic properties of the Khobar aquifer in the eastern coast of Bahrain under the project "Aquifer C Investigations". Five wells were drilled into the Khobar aquifer. They were fully tested and the data were analysed using numerous methods of analysis. In general, the results show that the Khobar transmissivity values in the eastern coast are substantially lower than those in the western and northern coasts obtained from previous investigations. A transmissivity range of between 450 to 3,600 m^2 day^{-1} was computed. Permeability values derived from the tests were found to vary from 46 to 350 m day^{-1}. Storage coefficients calculated for wells 1121 and 1122 using the tidal efficiency method gave values of 1.0×10^{-4} and 2.1×10^{-5}, respectively. Selected transmission and storage properties of the Khobar aquifer in the eastern coast are given in Table 3.3.

Figure 3.21 shows the transmissivity distribution in the Khobar aquifer. Despite that the map fails to reveal any identifiable pattern, which is not surprising for an aquifer of such a

Table 3.2 Selected hydraulic properties of the Khobar aquifer (tabulated after GDC (1980b))

Well no.	Location	Transmissivity (m^2 day^{-1})	Permeability (m day^{-1})	Storage coefficient (dimensionless)	Remarks
BT01K	Sadad	41280	1529 (27)	---	Mean of transient and steady-state methods (Jacob, Theim and Logan approx.) corrected for well loss.
BP05K	Saar	730	21 (35)	5.1×10^{-5}	Steady-state (Logan approx.) uncorrected for well loss. Storage coefficient obtained by tidal efficiency method.
BT10K	Wasmiyah	14530	377 (38.5)	8.8×10^{-5}	Steady-state methods (Theim, Logan approx.). Storage coefficient obtained by tidal efficiency method.
BT08K	Tubli	11950	351 (34)	---	Steady-state methods (Logan approx. and Brereton). Mean transmissivity. Corrected for well loss.

Note: Permeability is cut section, and bracketed figures are the aquifer cut section used to derive these estimates.

Table 3.3 Selected transmission and storage properties of the Khobar aquifer (adopted from GDC, 1983a)

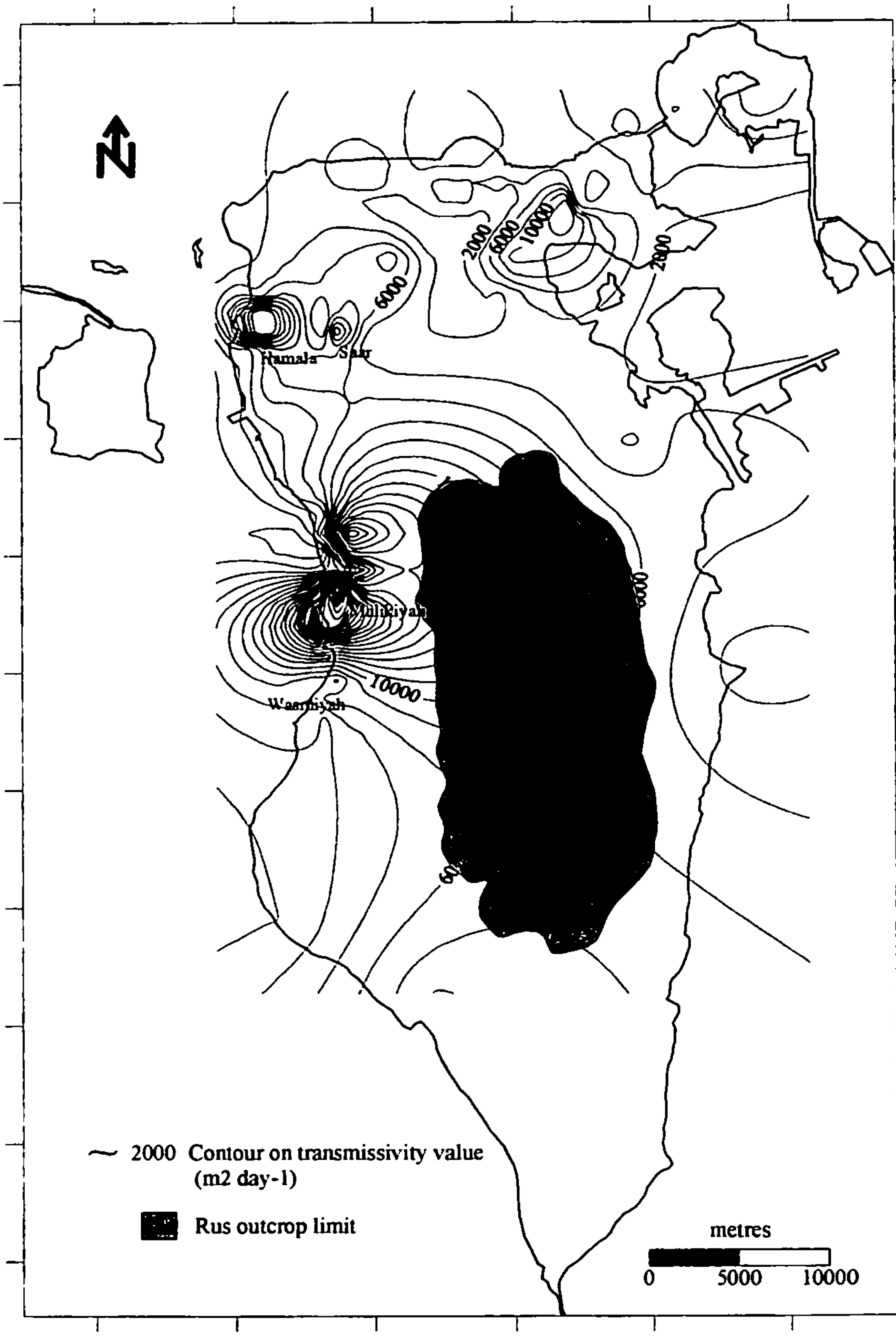
Well no.	Location	Transmissivity (m^2 day^{-1})	Permeability (m day^{-1})	Storage coefficient (dimensionless)	Remarks
1121	Ras Abu-Jarjur	3600	350 (10.3)	1.0×10^{-4}	Mean of transient and steady state analysis (Logan approximation)
1123	Ras Hayyan	1350	90 (15)	---	Mean of transient (Jacob and Theis Recovery) and steady state (Logan approximation).
1117	North Sitra	450	13 (35)	---	Logan approximation method.
1124	Hid (Asry)	1610	46 (35)	---	Logan approximation method.

Notes:

[1] Permeability values are cut section estimates.

[2] Bracketed figures are effective aquifer thickness for wells 1121 and 1123, and cut sections for wells 1117 and 1124.

Figure 3.21 Contours map of the transmissivity distribution in the Khobar aquifer



fractured nature, it suggests some structural control on the transmissivity. Khobar transmissivities increase a little towards the crest of the dome, and decrease towards the synclinal areas. The higher values in the structural highs seem to reflect fracturing along the dome axis. Transmissivity values also exhibit an increasing trend down the west coast near Zallaq-Wasmiyah area. The anomalously low transmissivities in Hamala-Saar, and Malkiyah-Dar Kulaib areas are probably associated with the depositional and structural phenomena that have been discussed earlier.

3.4.2 The Rus - Umm Er Radhuma Aquifer System

The Rus porosity is mainly developed in rock matrix and intergranular spaces, except where the formation has undergone extensive evaporite solution and reduction in the shale thickness, which normally results in solution collapse and the development of cavity and joint enlargement features (GDC, 1980b). Therefore, the anhydrite-shale Rus in the west and north of Bahrain is of low permeability, and is more likely to behave as an aquitard. Conversely, the non-anhydritic residual Rus in the central, north central, and east of Bahrain acts as an aquifer dominated by secondary permeability, and appears to have similar hydraulic characters to those of the upper part of Umm Er Radhuma. As pointed out by GDC (1980b), the dominant secondary permeability within the Rus - Umm Er Radhuma aquifer is manifested by the low permeability of the aquifer's core samples, and caliper and flow log evidence.

The Umm Er Radhuma is mainly a dolomitised limestone. Dolomitisation and dissolution processes have produced joints, fissures, and a vuggy intergranular porosity in various sections of the aquifer, resulting in high transmissivities (GDC, 1980b). Evidence from the middle and lower parts of the formation demonstrate distinct lithologic and hydraulic characteristics. The lowermost section of the Umm Er Radhuma, in particular, has a very low porosity, reflecting the change in lithology to argillaceous limestone towards the contact with the Aruma shale.

BAPCO have conducted a few specific capacity tests on wells tapping the upper part of the aquifer (mainly the Rus section). Their discharge and drawdown data were analysed by GDC using the Logan approximation method to derive transmissivity and permeability estimates, as listed in Table 3.4. The measured transmissivities and permeabilities range from 110 to 13,627 m^2 day^{-1}, and from 2.1 to 126 m day^{-1}, respectively. Such a wide range clearly reflects the lithologic complexity within the Rus section.

Tests performed by GDC on wells completed into various intervals of the Rus - Umm Er Radhuma aquifer have shown transmissivity values in the range from 9.2 to 40,000 m^2 day^{-1} (Table 3.5), with an average value of 5,975 m^2 day^{-1}. The extremely low transmissivity value of 9.2 m^2 day^{-1} seems realistic because it is reported from a well located in the western coast that penetrated only the upper part of the Rus section that contains considerable aggregates of anhydrite and shale. The cut section permeability was in the range of 0.2 to 513 m day^{-1}. A weighted mean permeability of 25 m day^{-1} for the entire thickness of the aquifer in the study area is adopted. In 1983, the Rus - Umm Er Radhuma aquifer was investigated as a potential source to feed the proposed reverse osmosis desalination plant. The pumping test results derived from this investigation are summarised in Table 3.6. As can be expected, the table indicates that the aquifer generally displays very high transmissivity, with tests conducted in the eastern coast showing transmissivity values relatively higher than those of the western coast.

Table 3.4 Selected Rus - Umm Er Radhuma hydraulic properties derived from BAPCO specific capacity data (after GDC, 1980b)

Well no.	Penetrated aquifer	Specific capacity (m^3/day/m)	Transmissivity (m^2 day^{-1})	Cut section (m)	Permeability (m day^{-1})
CWW 30	Rus	694	846	31	27
CWW 45	Rus	798	974	35	28
708	Rus-UER	11170	13627	128	106
860/861	Rus	2070	2525	20	126
882	Rus	90	110	52	2.1
925	Rus	864	1054	33	32

Notes: [1] Transmissivity determined by Logan approximation, no correction for well loss is applied.
[2] UER is Umm Er Radhuma.

Table 3.5 Transmission properties of the Rus - Umm Er Radhuma aquifer (adapted after, GDC, 1980b)

Well no.	Transmissivity (m^2 day^{-1})	Permeability (m day^{-1})	Cut section thickness (m)	Remarks
BP03R	9.2	0.2	55.5	Rus aquifer
BT04U	9420	59.6	158.0	
BS06U	2976	37.6	79.0	
BS07U	1210	31.0	39.0	
BS09U	2080	21.0	100.0	
BS11U	3500	50.0	69.6	Effective flow section about 42 m thick
BT14U	3000	18.4	163.0	Transmissivity is mean value of non-steady state
BP15U	63.0	1.0	62.0	Transmissivity uncorrected for well loss
BS16U	40000	513.0	78.0	
BS18U	2070	7.5	277.0	
BS19U	1400	40.0	35.0	Mean of steady state analysis adopted

Notes: [1] Transmissivities are adopted values from high and low estimates, derived using various methods of analysis.
[2] Permeability values are cut section

Table 3.6 Selected transmission properties of the Rus - Umm Er Radhuma aquifer (adapted after GDC, 1983a)

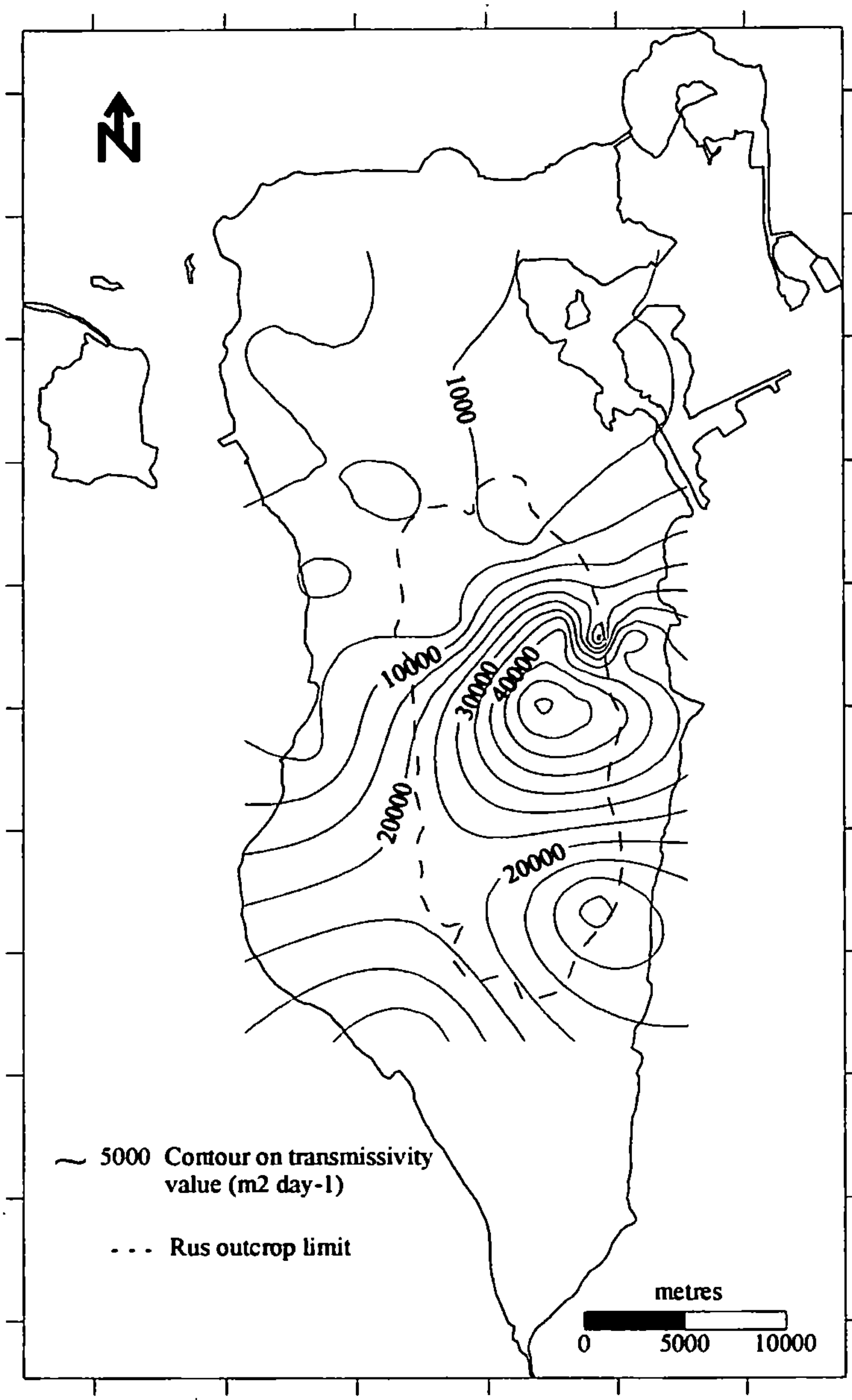
Well no.	Type of test	Method of analysis	Transmissivity (m^2 day^{-1})	Permeability (m day^{-1})	Remarks
1118	Constant discharge	Theis recovery	1010	20	Rus aquifer
1114	Specific capacity	Modified Logan	44000	---	Rus - Umm Er Radhuma aquifer
1120	Step-drawdown	Modified Logan	76000	---	Rus - Umm Er Radhuma aquifer
1119	Specific capacity	Modified Logan	49000	---	Rus - Umm Er Radhuma aquifer
1115	Specific capacity	Logan approximation	500	28	Umm Er Radhuma isolated section - not corrected for well loss
1126	Constant discharge	Modified Logan	8400	46	Rus - Umm Er Radhuma aquifer-west coast
BT04U	Step-drawdown	Jacob approximation	7862	50	Rus - Umm Er Radhuma aquifer-west coast

Note: Permeability values derived are cut section permeabilities.

The available transmissivity data permitted the construction of a transmissivity distribution map for the Rus - Umm Er Radhuma over the study area, as shown in Figure 3.22. The general pattern indicates that the spatial distribution of transmissivity in this aquifer is controlled by both tectonic and non-tectonic structures (collapse structures and kartsification features) resulted from anhydrite solution and shale removal from the Rus section, and from dissolution of carbonate rocks by flow of shallow groundwater. The highly kartsified and commonly non-anhydritic Rus - Umm Er Radhuma along the domal structure, and in the eastern and southeastern coasts show higher transmissivity values. The aquifer is also very transmissive in the southwestern coast, probably because of anhydrite dissolution, although lithologic well logs in those areas show that the Rus contains considerable aggregates of shale-claystone. A decreasing trend is notable towards the west and north off-the-dome synclinal areas, in conformity with the well-documented presence of significant amounts of shale-anhydrite in the Rus section in these areas.

The highly transmissive, fractured nature Rus - Umm Er Radhuma aquifer normally exhibits rapid drawdown and low storage properties. As indicated earlier, transient drawdown data are absent in most of the pumping tests carried out in the study area, implying that limited information is available on the storage properties of this aquifer. Storage coefficients determined for the confined Rus - Umm Er Radhuma aquifer from the tidal efficiency method varies from 1.5×10^{-4} to 3.0×10^{-4}, with an average value of 2.25×10^{-4} (GDC, 1980b). Zubari (1987) reported specific yield values for the aquifer under unconfined condition in the range of between $2.5 \times 10^{-1} - 3 \times 10^{-1}$. Zubari and Khater (1995) calculated the aquifer specific yield for the unconfined Rus - Umm Er Radhuma at the central part of Bahrain, using change in head per change in volume

Figure 3.22 Contour map of the transmissivity distribution in the Rus - Umm Er Radhuma aquifer



analysis for the period 1984 – 1993, at about 2.0×10^{-1}. Table 3.7 summarises the storage properties of the Rus - Umm Er Radhuma aquifer in the study area.

3.4.3 Aquitard Hydraulic Properties

The hydraulic properties of the confining layers are poorly defined because the data available are very scant. Most of the available data are derived from analysis of core samples. As referred to previously, the Neogene functions as aquifer or aquitard depending on the percentage of claystone within its section. This percentage ranges from 50 % to 100 % of the total thickness, with a mean cut section vertical permeability of 10^{-5} – 10^{-2} m day^{-1}, and a leakance coefficient of 10^{-8} to 6×10^{-4} (GDC, 1980b). The Orange Marl aquitard leakance coefficients, also measured from core samples, gave values in the range from 10^{-5} – 1×10^{-3} m day^{-1}. The Shark Tooth Shale, which practically separates the Dammam Aquifer System from the Rus - Umm Er Radhuma Aquifer System has a vertical permeability of 3.8×10^{-4} m day^{-1}. However, this value was based on the analysis of only one core sample obtained for this aquitard unit from a well located in Saar area just east of the west coast.

The percentage of the anhydrite and shale within the Rus section, as already established, determines its behaviour as aquitard or aquifer. When it acts as aquitard, the vertical permeability of the Rus shale ranges from 1.7×10^{-7} m day^{-1} to 4.2×10^{-5} m day^{-1}, and averages 8.1×10^{-6} (GDC, 1980b). Analysis of core samples carried out during the Umm Er Radhuma Study produced vertical permeability values of Rus samples consisting of anhydrite in the range of 1.2×10^{-6} to 1.4×10^{-3} m day^{-1}, with an average value of 4.7×10^{-4} m day^{-1}. Core measurements of the Aruma aquitard samples yielded an

Table 3.7 Storage coefficient estimates for the Rus - Umm Er Radhuma aquifer (after GDC, 1980b; GDC, 1983a)

Well no.	Location	Method of estimates	Storage coefficient (dimensionless)	Remarks
BS06U	Saar	Tidal efficiency	1.47×10^{-4}	
1118	West of Askar	Tidal efficiency	2.1×10^{-4}	Umm Er Radhuma - confined
1118	West of Asker	Tidal efficiency	2.8×10^{-4}	Rus - Umm Er Radhuma - fully confined

average Aruma shale vertical permeability of 0.08 m day^{-1}, and a slightly higher average value of 0.1 m day^{-1} for the Aruma argillaceous limestone. The aquitards' hydraulic characteristics in the study area are presented in Table 3.8.

3.5 Piezometric Levels

As previously indicated and illustrated in Figure 3.1, regional groundwater flow has a north-west, south-east direction from the outcrop area in Saudi Arabia mainland towards the discharge area in Bahrain. Hydraulic gradients are low, of the order of 0.0001 (GDC, 1979). Piezometric levels are generally higher in the deeper aquifers.

The aquifer systems piezometry in the study area has been discussed in terms of a series of piezometric levels and drawdown contour maps substantiated by hydrographs analysis of selected observation wells. The main source of information for the aquifers piezometry is the observation data files of the WRD, which maintains an observation well network consisting of 72 wells, of which 65 are currently (2000) operational. Pre-development piezometric contour maps were reproduced from the regional maps prepared by GDC as part of the Umm Er Radhuma Study. Piezometric head data for 1997 are considered as the latest update for this study, because the efficiency of the observation network in terms of number of observation wells and quality of data collection and analysis has markedly degraded since then.

3.5.1 The Dammam Aquifer System

The groundwater flow pattern in the Dammam aquifer strictly reflects the regional flow regime. Throughflow recharge towards Bahrain takes two preferential pathways, north and south of Umm Nassan Island, suggesting that this island may have some structural

Table 3.8 The confining layers hydraulic properties (adapted after GDC, 1980b; 1983a)

Aquitard unit	Vertical permeability ($m\ day^{-1}$)	Leakance coefficient ($m\ day^{-1}$)	Remarks
Neogene claystone	$10^{-5} - 10^{-2}$	$10^{-8} - 6 \times 10^{-4}$	Core analysis estimates
Orange Marl	---	$10^{-5} - 8 \times 10^{-3}$	Core sample analysis
Shark Tooth Shale	3.8×10^{-4}	---	Core analysis estimate in the western coast
Rus shale	$1.7 \times 10^{-7} - 4.2 \times 10^{-5}$	---	Core sample analysis
Rus anhydrite	$1.2 \times 10^{-6} - 1.4 \times 10^{-3}$	---	Core analysis estimates
Aruma shale	0.08	---	Core analysis – (GDC, 1983a)
Aruma argillaceous limestone	0.1	---	Laboratory determination – (GDC, 1983a)

control on groundwater flow (GDC, 1979). Another flow path crossing Al-Jarim offshore area, and extending to the northeastern corner of Bahrain around Muharraq Island, is demonstrated by the early piezometric maps (Godfrey, 1958; Wright, 1967; Italconsult, 1971). The Italconsult map, in particular, shows a groundwater mound centred around Fasht Al-Jarim. Anomalies to the regional flow pattern occurs in the north-central part of Bahrain around Aali-Salmabad area where positive heads gradient are evident consequent upon the upward movement of saline groundwater from the Rus - Umm Er Radhuma Aquifer System (GDC, 1980b). Piezometric levels decrease to about sea level along the west coast between Al-Wasmiyah and Al-Mummattalah, and on the east coast south of Sitra Island where the Dammam aquifers are believed to crop out below sea level (Wright *et al.*, 1983). Active flow is believed to be restricted further down the west coast beyond Ras Al-Jazair, and in the eastern and southeastern offshore area along the saline wedge.

Historical data have shown that the Alat and Khobar aquifers follow almost a similar piezometric pattern. Piezometric data on the Alat Limestone are available from the aquifer's monitoring network, which was established in 1985. An Alat piezometric level contour map for the pre-1924 period (the predevelopment condition) is shown in Figure 3.23. This map was synthesised by GDC by extrapolating the early static head data (1939 to 1953) on the basis of hydraulic, hydrochemical and archaeological evidence, to represent the time where the Dammam aquifer was most probably at steady state condition. It shows an Alat piezometric level of between 4 – 4.5 m at Umm Nassan and generally exceeding + 6 m at the offshore area between Bahrain and Saudi Arabia mainland. Around Sitra Island, the Alat piezometric level was between 1 to 2 metres.

A piezometric contour map for the Alat Limestone aquifer in 1997 is shown by

Figure 3.23 Alat Limestone aquifer early piezometry (reproduced after GDC, 1980)

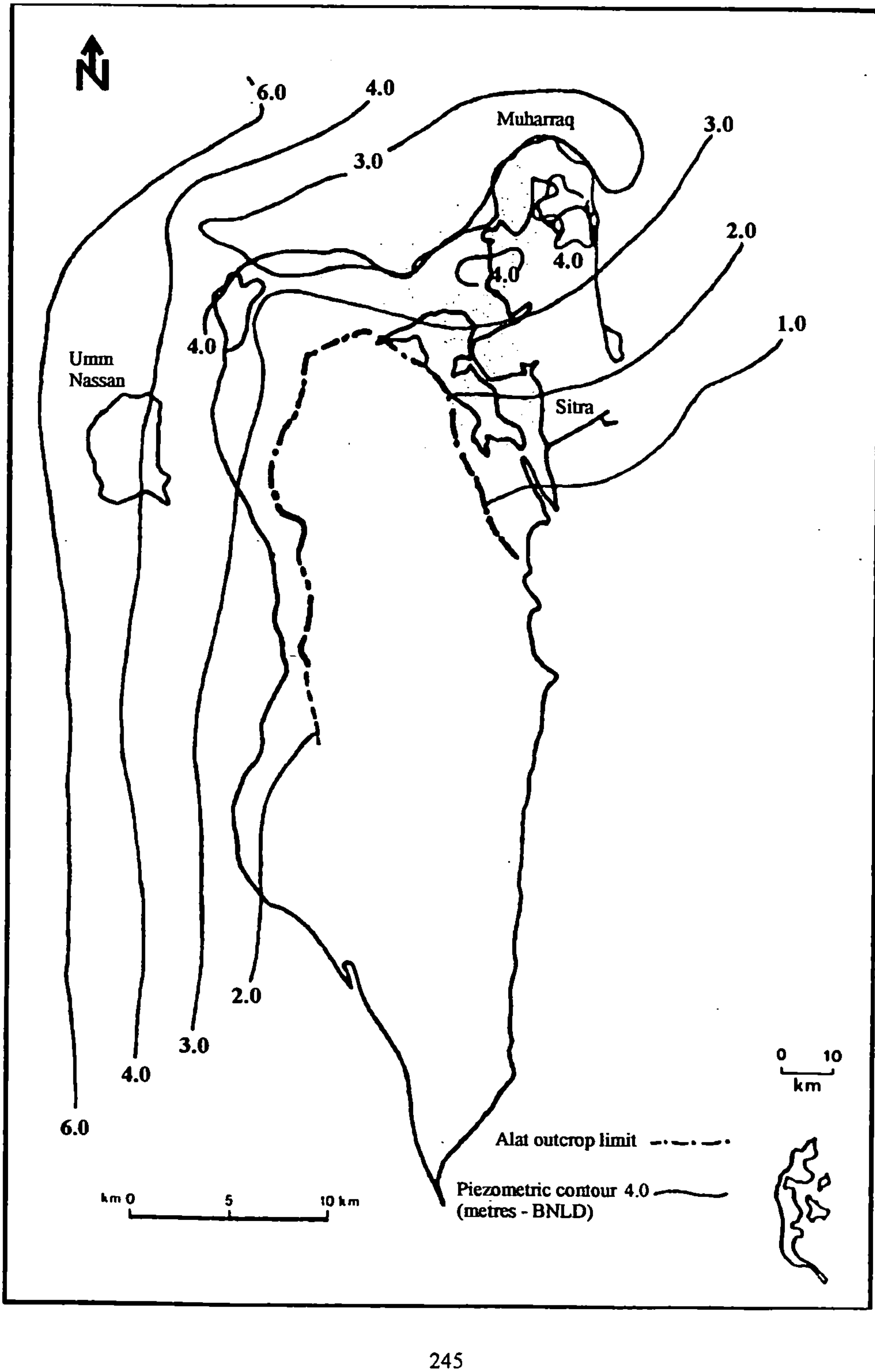


Figure 3.24. The data used to derive this map are tabulated in Table B-1 of Appendix B. These are contours of annual average piezometric heads reduced to the BNLD, with no tidal correction. The low mound developed in the western coast near Hamala and Janabiyah reflects localised groundwater build up attributed to present-day recharge from rainfall and irrigation returned flow over the unconfined part of the aquifer. Apart from this anomaly, the trend seems to be consistent with the regional pattern, with average heads of about 1 m and 0.3 m at Umm Nassan and Sitra Islands, respectively. Comparison of the Alat pre-1924 (Figure 3.23) and 1997 piezometric maps indicates that the aquifer has lost between 1.6 – 5.2 m of its piezometric head. Maximum water level decline can be observed in the vicinity of Umm Nassan Island, whereas a lower decline in heads was recorded in Sitra Island.

Figure 3.25 is a drawdown map, which illustrates the piezometric level changes in the Alat aquifer over the period from 1987 to 1997 (piezometric level data for 1987 are also given in Table B-1). The figure indicates that the aquifer heads have dropped within a range of 0.4 – 2.0 m, with an average decline of about 1.2 m. Maximum drawdown of between 1.8 to 2.0 m is recorded in the northern coast; the minimum is about 0.4 m, and is observed in the eastern and southwestern coasts. In the western area including Umm Nassan Island, the Alat piezometric levels have dropped by an average of 1.2 m. Water level decline of up to 1.8 m is recorded in Manama and Muharraq areas.

Water level trends of the Alat aquifer are represented by the hydrograph of well WRD 1102 located at Budaiya in the northwestern coast as shown by Figure 3.26. The hydrograph exhibits both seasonal water level fluctuations, owing to variation in seasonal abstraction patterns, and long-term decline. The anomalous mound in 1993 obviously

Figure 3.24 Piezometric contour map of the Alat Limestone aquifer 1997

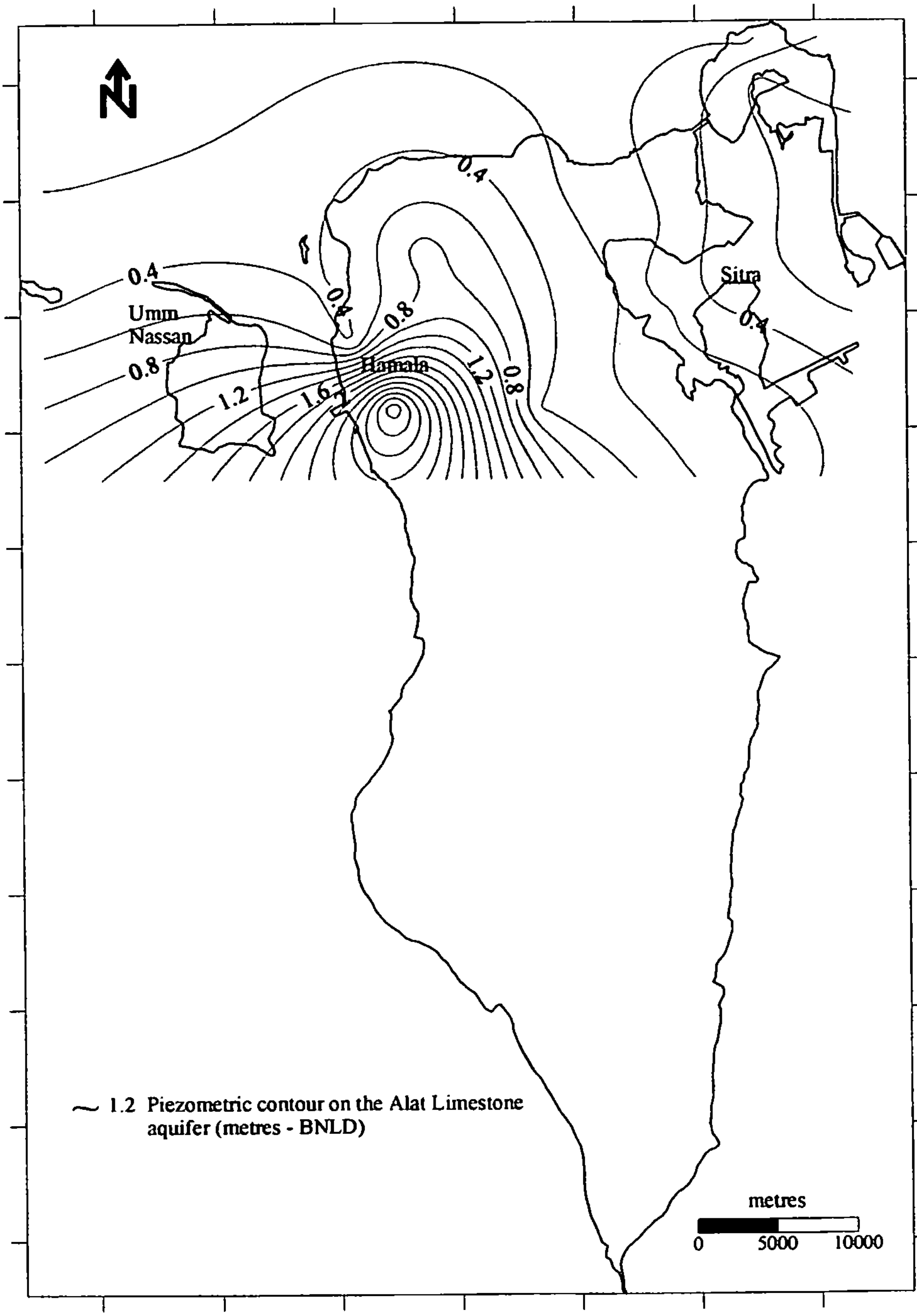


Figure 3.25 Piezometric head difference of the Alat Limestone aquifer 1987 - 1997

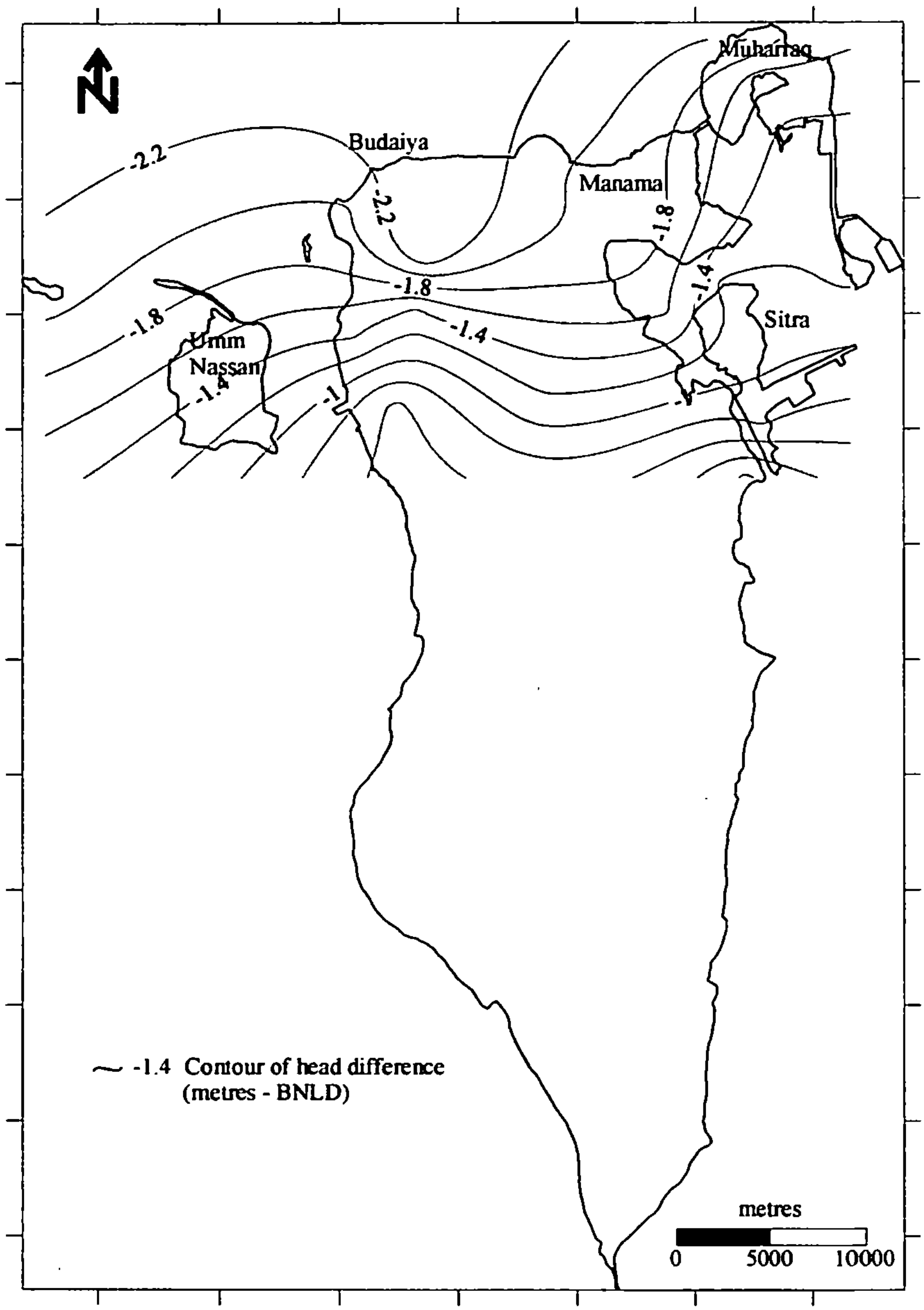
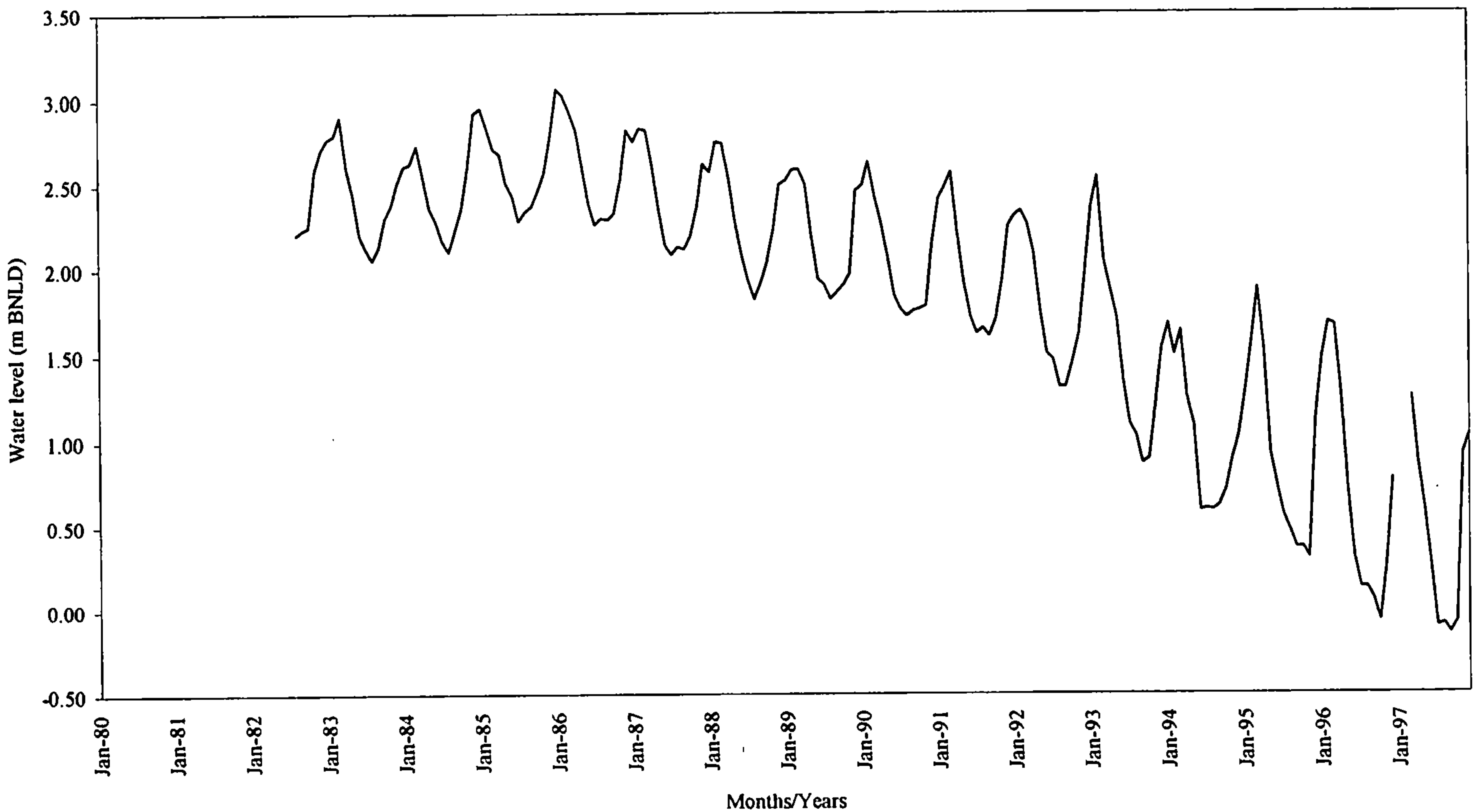


Figure 3.26 Well hydrograph showing the water level trend in the Alat Limestone Aquifer 1983 - 1997



reflects the exceptional monthly rainfall (77.7mm, see Table A-1 of Appendix A) in December 1992. Water levels declined at an average rate of about 0.29 m/year over the period 1987 – 1997, against a calculated annual decline rate for the aquifer of about 0.14 m. Over the unconfined part of the aquifer, however, water level seems to be slightly affected by rainfall and possible input from irrigation returned flow as will be discussed later.

An early piezometry map (prior to 1924) was reconstructed for the Khobar aquifer by GDC using the same extrapolation technique applied to synthesis the Alat predevelopment map, as shown in Figure 3.27. The map shows head exceeding + 6 m at Umm Nassan Island, decreasing to between 2 – 2.5 m in the vicinity of Sitra Island. The Khobar piezometric heads have declined by about 0.5 m (de Mestre and Haines, 1958) and by some 4 to 5 m (GDC, 1980b) since the pre-development stage, when the aquifer was most probably at a steady state.

By comparing the two predevelopment piezometric contour maps (Figures 3.23 and 3.27), it can be inferred that the Khobar piezometry exceeds that of the Alat by between 0.8 to 1.0 m during the 1960s and 1970s, and perhaps most of the 1980s; however, the difference in head between the two aquifers was considered insignificant, indicating more head loss in the Khobar than in the Alat (Wright, 1967; GDC, 1980b; Zubari, 1987). The Khobar piezometry for the year 1997 is given in Figure 3.28. The trend alarmingly shows that most of the observed heads are below the BNLD datum. Piezometric lows, but at least still positive with respect to the datum, are evident around the eastern and northeastern coasts, and are probably due to the recent relative control on groundwater abstraction in this area. Higher heads of up to + 2.4 m are centred on the north-central part of the study

Figure 3.27 Khobar aquifer early piezometry (reproduced after GDC, 1980)

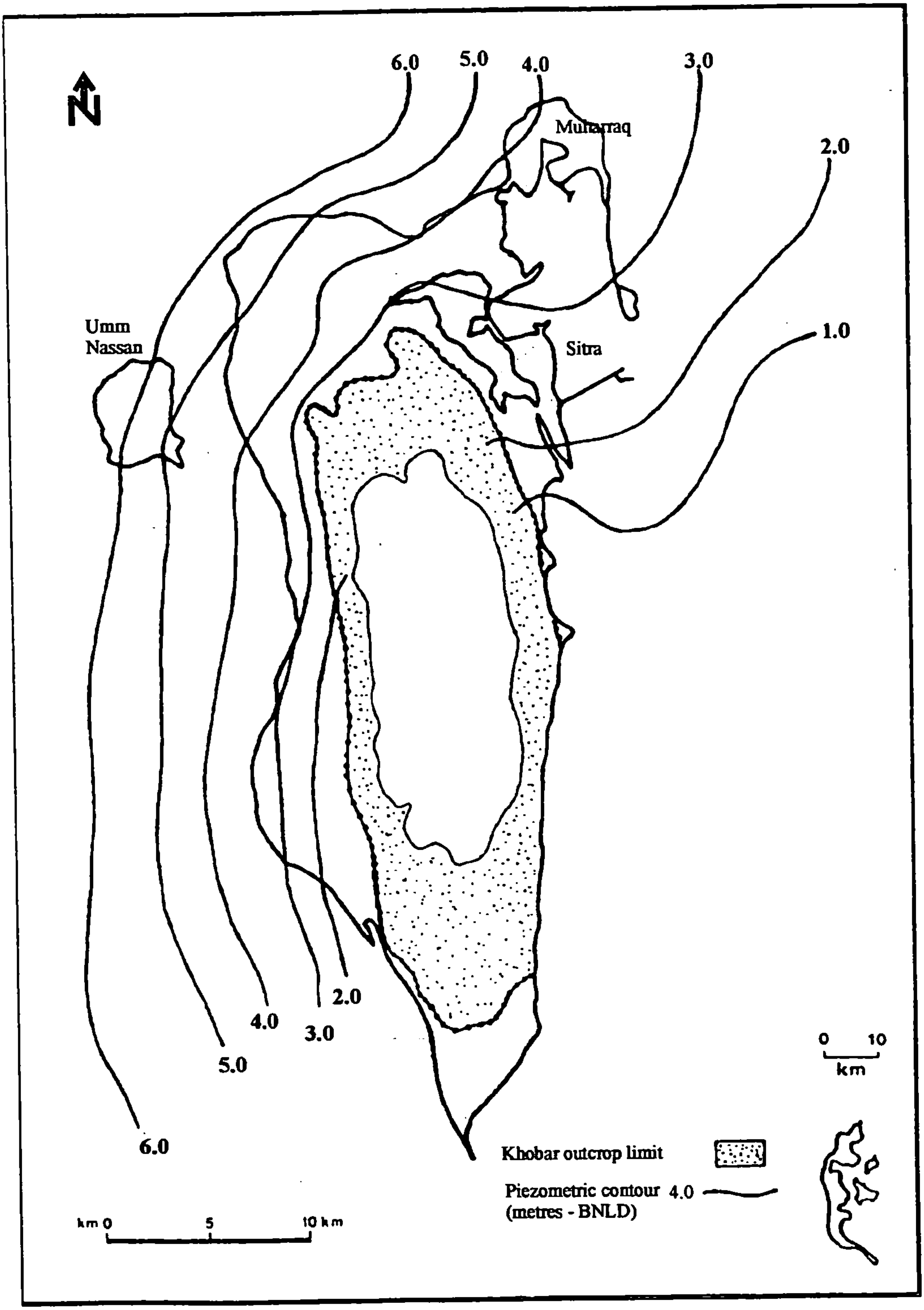
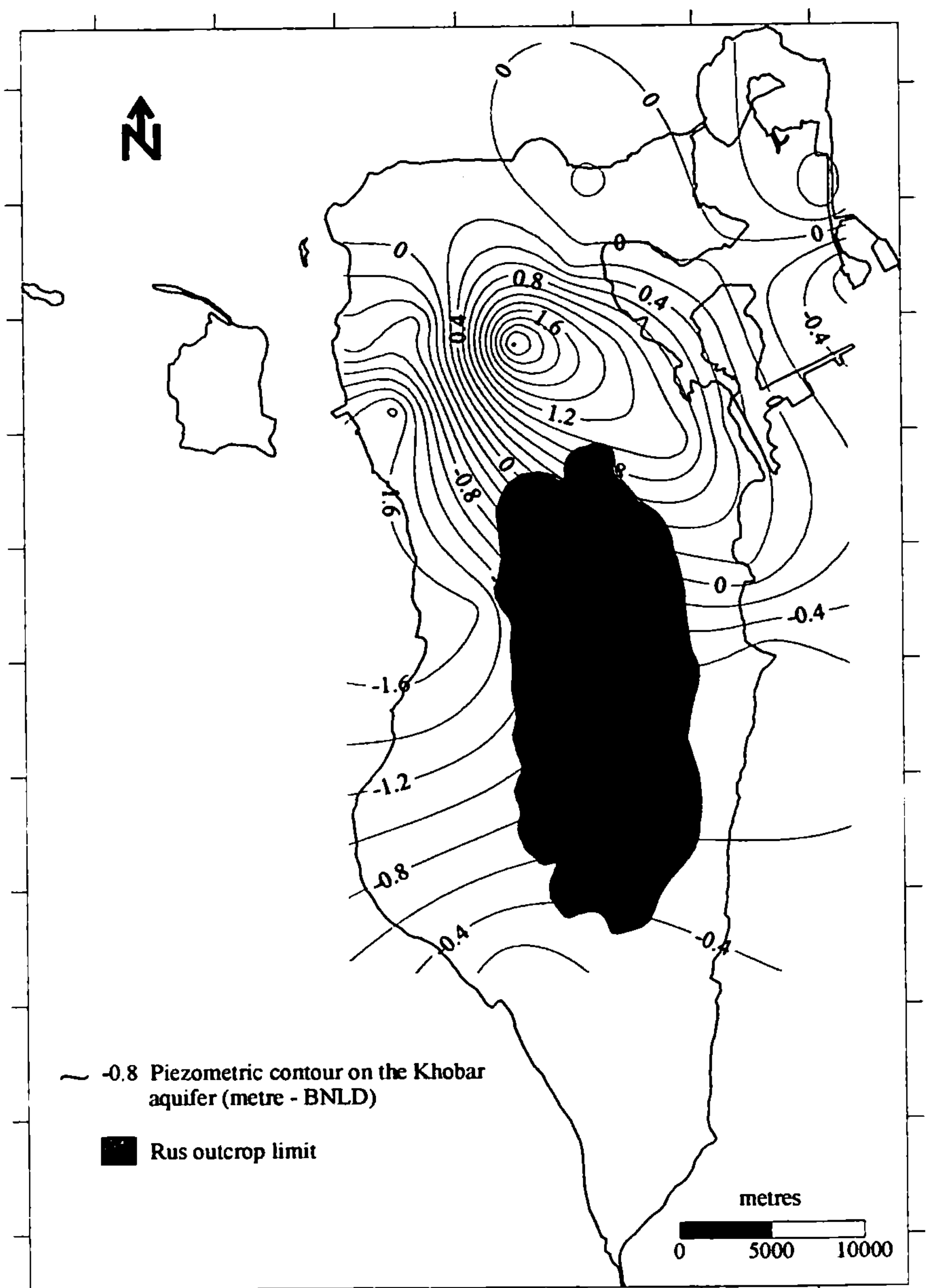


Figure 3.28 Piezometric contour map of the Khobar aquifer 1997



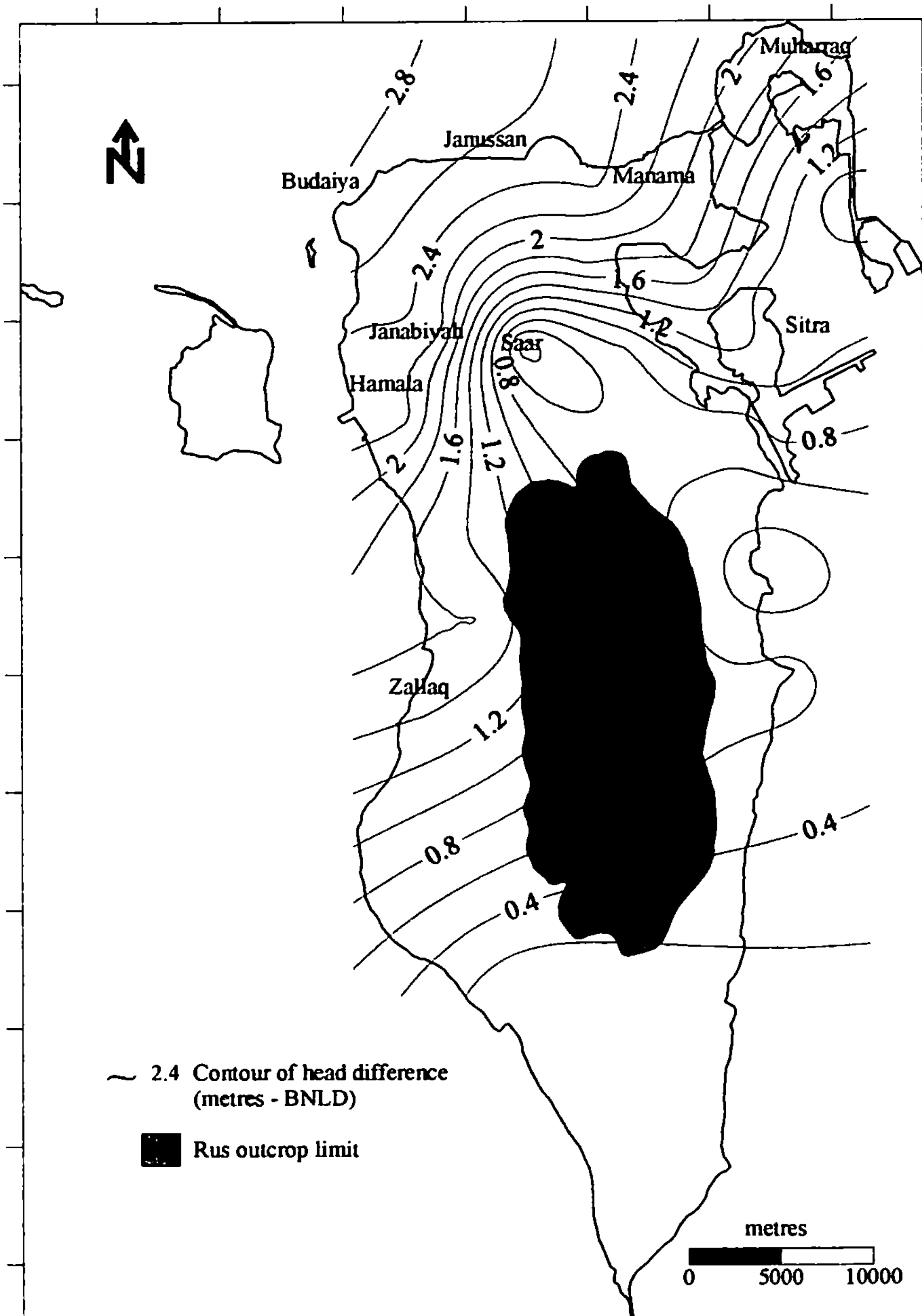
area. These are positive heads resulted from pressure release from the deeper Rus - Umm Er Radhuma aquifer, where aquitard materials are largely absent.

The piezometric level distribution of 1997 clearly shows that the aquifer has lost between 2.5 to 7.5 m of its predevelopment levels. It is of interest to note that, if this distribution is compared with the Alat piezometry for the same year (Figure 3.24), it can be deduced that the latter has generally higher heads by at least 0.4 m. This is not surprising since most of the Dammam groundwater abstraction in the study area comes from the Khobar aquifer.

As illustrated by the drawdown map in Figure 3.29, the Khobar water levels showed a marked decrease between 1987 and 1997. The data used to generate this map are given in Appendix B, Table B-2. The figure demonstrates that the decline was at its maximum near the major pumping centres, particularly those located in Manama, Muharraq, and the northern coast. In the vicinity of Janusan and Budaiya villages, for instance, water levels have dropped from as high as 2.8 m to between 0.3 – 1.0 m.

A significant cone of depression can be observed near Janabiyah, and Hamala-Saar area. This drawdown can be interpreted as being a consequence of a localised over-abstraction from the aquifer during the late 1980s and early 1990s. Apparently, the low transmissivity of the Khobar in this area contributes greatly to this decline. Similar over-development effects have resulted in a localised drawdown further west in the vicinity of Wasmiyah area, with a subsidiary cone of depression developed around Zallaq, possibly as a result of localised pumping to supply Awali Town with its domestic water.

Figure 3.29 Piezometric head difference of the Khobar aquifer 1987 - 1997



It should be noted, however, that the rate of decline in the southwestern area over the period from 1987 to 1997 had decelerated compared with the trend observed by Al-Noaimi (1993) during late 1980s. This area, in particular, has experienced a considerable decline in the Khobar water level, coupled with a marked increase in salinity between the late 1980s and early 1990s (Al-Noaimi, 1993). This decline seems to reflect a sudden stress imposed on the aquifer between 1987 and 1991; therefore the best that can be said about this deceleration is that it reflects possible reduction, and perhaps halting of groundwater withdrawal in response to a salinity increase. Generally speaking, the drawdown map shows relatively less significant falls in head in the eastern areas of between 0.4 to 0.7 m. This is ascribed to the controlled abstraction measures and abandonment of agricultural activities in this part of the study area.

The hydrograph of observation well WRD 1004 completed in the Khobar aquifer and located south of Saar village is shown in Figure 3.30. Analysis of this hydrograph also shows a systematic pattern of seasonal variations and a steady long-term water level decline, although there are exceptions in years 1993 and 1997. Water level, in general, varies with seasonal pumpage, although this relation is somewhat masked in areas of heavy withdrawal. The average decline rate at this well is 0.36 m per annum, while the aquifer as a whole is declining at a rate of 0.13 m per annum from 1987 to 1997. This decline in head has shown to be associated with salinity increase and cessation of spring flows, as explained in the sections that follow.

3.5.2 The Rus - Umm Er Radhuma Aquifer System

The early piezometry map for the Rus - Umm Er Radhuma aquifer is shown in Figure 3.31. The map shows a head of about + 4 m at Umm Nassan Island and the eastern

Figure 3.30 Well hydrograph showing the water level trend in the Khobar Aquifer 1980 - 1997

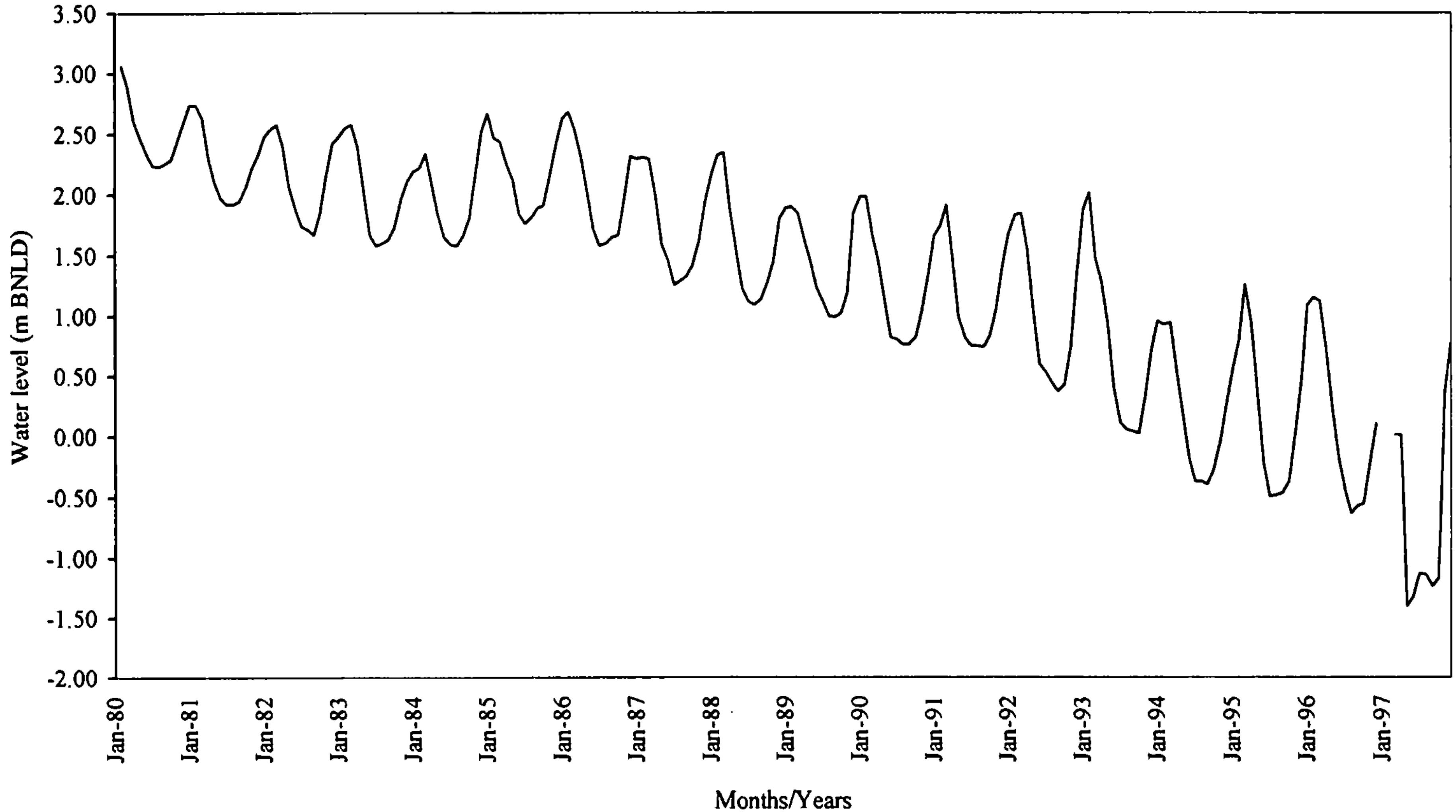
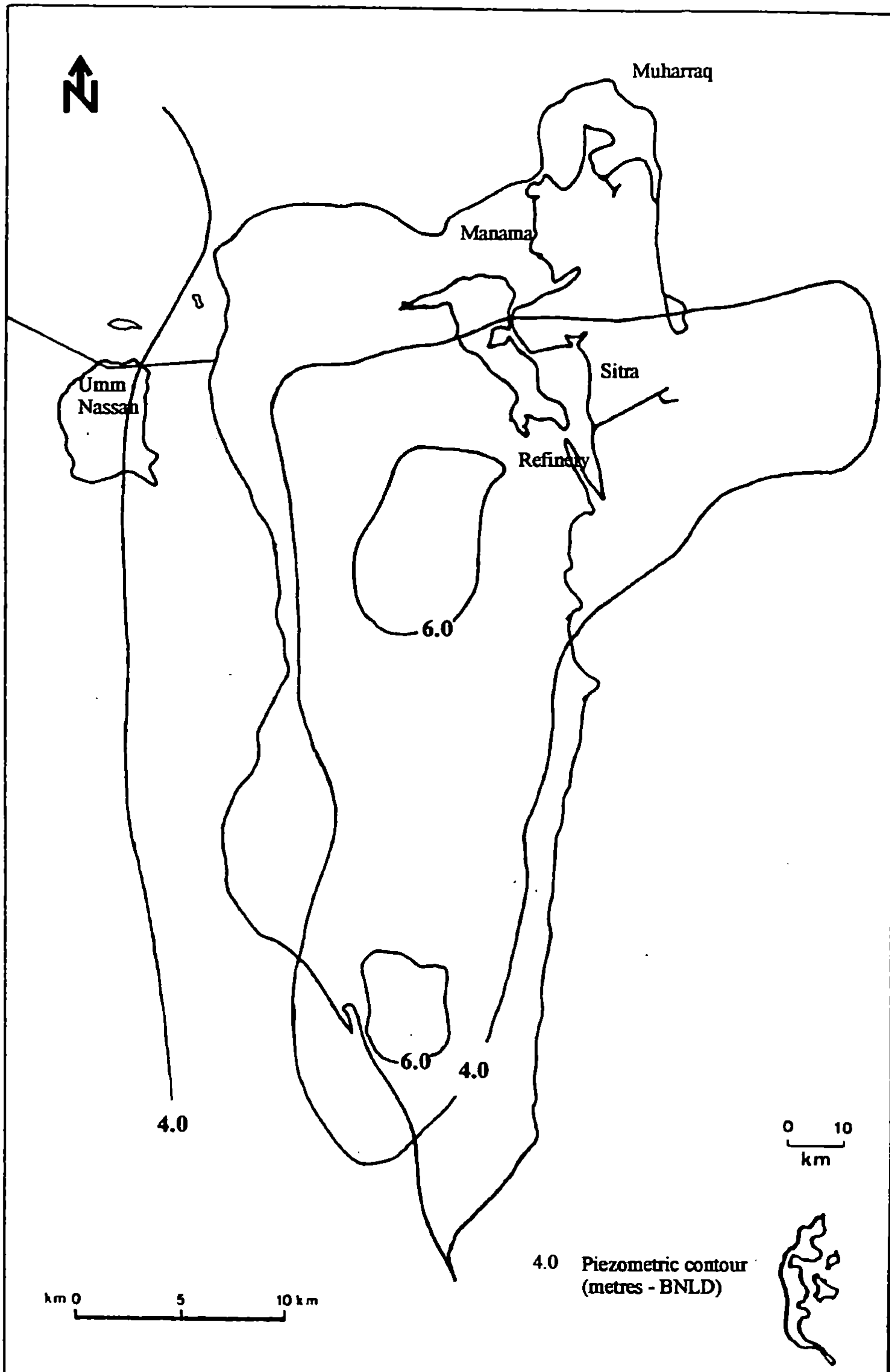


Figure 3.31 Rus - Umm Er Radhuma early piezometry (reproduced after GDC, 1980)



coast, and notable piezometric highs of about + 6 m in the north-central and southern areas. As shown by GDC piezometric map of 1979, the aquifer water level had fallen by between 0.5 to 1 m in the eastern area, probably in response to the major withdrawal from this aquifer around Bahrain Refinery area. The trend in the north-central and southern parts had almost remained constant, whereas the western area has recorded a water level decline of about 0.7 m.

Table B-3 of Appendix A, lists the Rus - Umm Er Radhuma aquifer piezometric data as well as the calculated drawdowns for the period from 1987 to 1997. These data are also annual average piezometric levels with respect to the BNLD datum, but not corrected for fresh water head for deeper lower Umm Er Radhuma penetration. This point warrants further attention as GDC (1980b) noticed that piezometric heads are often depressed by high salinity of the formation fluid in wells cutting deep into the Umm Er Radhuma Formation.

These data were used to compile a piezometric contour map for 1997 and a drawdown map over the period 1987 – 1997, as shown in Figures 3.32 and 3.33. During the period from 1924 to the year 1997, the aquifer has lost between 2.2 m to 5 m of its head. The major water level lowering has been recorded since 1984 in response to the large-scale abstraction from Ras Abu-Jarjur wellfield (averaging at about 25.6 Mm^3 $year^{-1}$) to feed the reverse osmosis desalination plant with its raw water. The water level trend (excluding the Hamala case, which represents an obvious anomalous that would be highlighted latter) in Figure 3.32 reveals that the aquifer possesses a maximum head of about 1.9 m in the southwestern coast, and a minimum of about 1 m in the vicinity of the wellfield area.

Figure 3.32 Piezometric contour map on the Rus - Umm Er Radhuma aquifer 1997

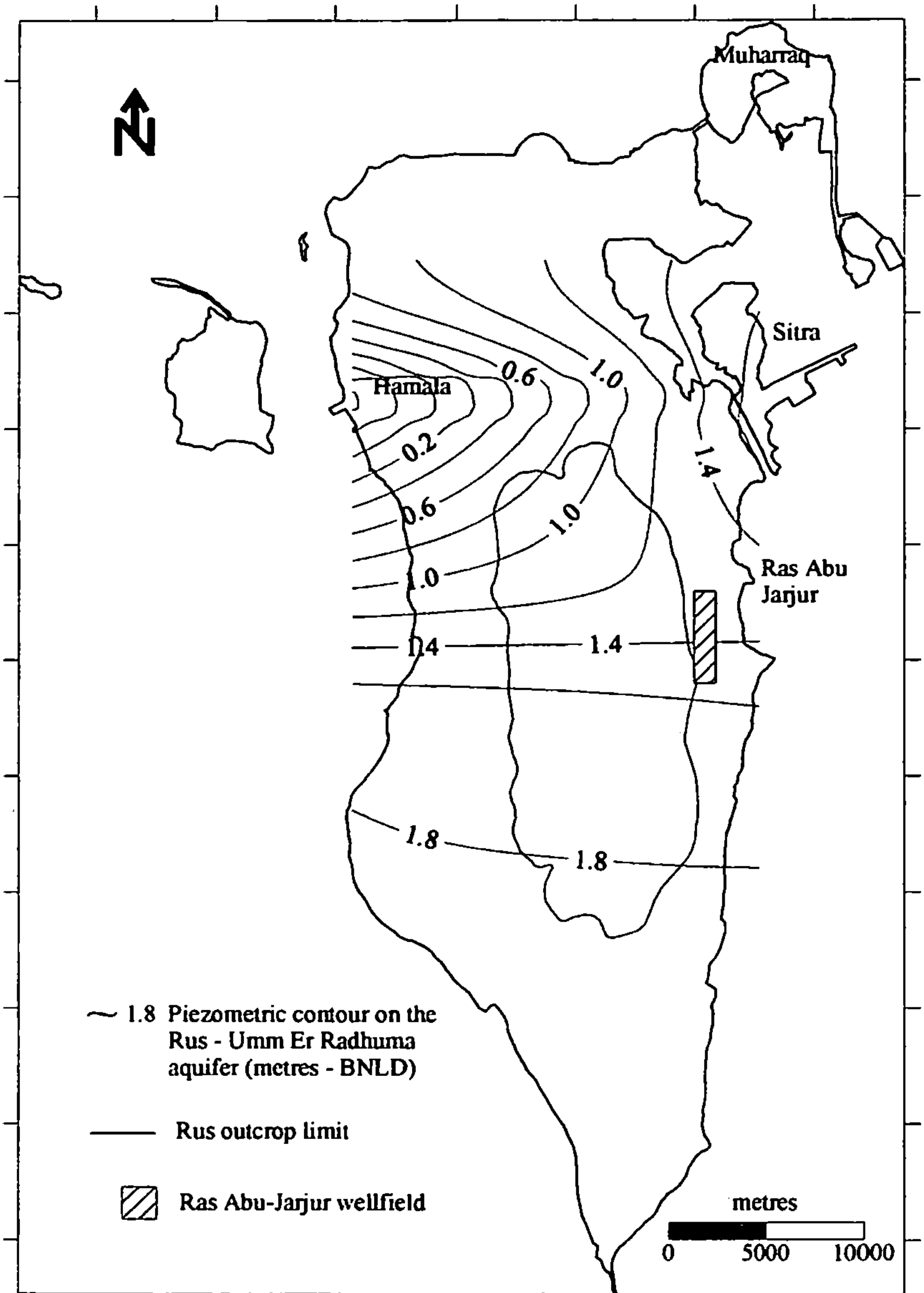
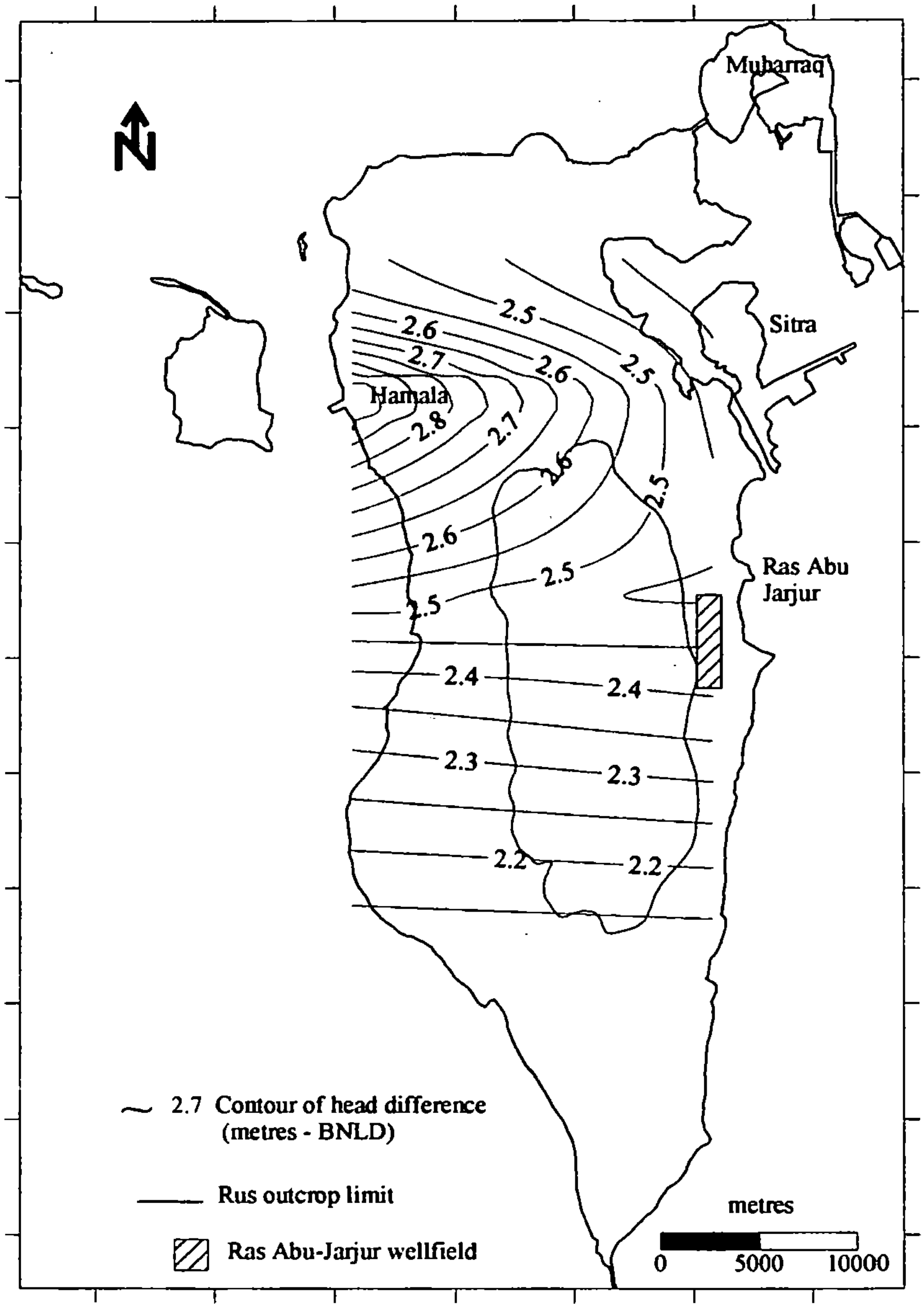


Figure 3.33 Piezometric head difference of the Rus - Umm Er Radhuma aquifer 1987 - 1997



The drawdown pattern in Figure 3.33 indicates that water levels in the Rus - Umm Er Radhuma aquifer have continued to decline steadily. Greater head losses of between 2.4 to 2.6 m are observed around the wellfield area. Relatively, less drawdown is discernible to the west of the wellfield, and is coincident with the points of injection (averaging at about 7 Mm^3 $year^{-1}$ since 1960) of the oil-associated water into the aquifer (Zubari, 1994). The observed piezometric levels have dropped by a maximum of about 2.8 m in Hamala area, and a minimum of about 2.1 m in the southwestern region. The Hamala case referred to earlier is probably an anomaly caused by, according to Zubari (1994), water level being depressed by migration of high salinity brine. The overall average decline during the period under consideration is estimated at 2.45 m.

The vertical leakage from the Rus - Umm Er Radhuma aquifer to the Dammam aquifer is very important phenomenon because it is one of two major sources of saline water to the Khobar aquifer. This leakage is controlled by the vertical hydraulic gradient between the two aquifer systems, and also by the hydrogeologic behaviour of the Rus Formation. During the pre-development state (Figures 3.27. and 3.31), the heads in the two aquifers are thought to have been approximately equal (GDC, 1983a). The transient condition has witnessed over-exploitation from the Khobar aquifer, while abstraction from the Rus - Umm Er Radhuma has been negligible. This has resulted in a considerable lowering of the Khobar water level and, hence increased head difference between the two aquifers.

GDC (1980b) have shown that the heads in the Rus - Umm Er Radhuma exceed those of the Khobar by about 5.5 m, and 4 m, in Sitra and in the north-central area, respectively. In the western areas the Rus - Umm Er Radhuma aquifer had greater head by at least 5 m. The average overall head differential, as interpreted from their map, is estimated at approximately 4.2 m.

The map in Figure 3.34 shows the piezometric head differential between the Khobar and Rus - Umm Er Radhuma aquifers for the year 1997. Although this map is plotted from a few control points, it clearly shows that the head differences have been substantially reduced, owing to the heavy withdrawal from the Rus - Umm Er Radhuma aquifer since 1984. The head differential in Sitra is about 0.4 m, while that in the north-central area is around 1.3 m. In the western coast, the head difference between the two aquifers was still appreciable at about 2.8 m. The highest and lowest reductions in head difference were observed along the eastern coast and to the west of the wellfield, respectively, and are positively attributed to the Ras Abu-Jarjur abstraction and oily water injection. A more important consideration in this context is the head differential in the north-central area, which is the major local upflow zone. Generally, the difference in piezometric head between the Rus - Umm Er Radhuma and Dammam aquifer systems in this area had been reduced from about 4 m to about 1.4 m between 1979 and 1997. The average overall head difference for the year 1997 can be estimated at approximately 1.8 m. Indeed, this would minimise the contamination of the Dammam aquifers by upward movement of saline water.

The Rus - Umm Er Radhuma aquifer does not show pattern of seasonal variation but, as indicated earlier, it does exhibit long-term water level decline. This is illustrated by the hydrograph of observation well WRD 1114 located at the middle of the Ras Abu-Jarjur wellfield. The hydrograph (Figure 3.35) records a head decline at a rate of about 0.28 m per annum for the period 1987 - 1997, against a calculated average head drop for the aquifer of about 0.24 m $year^{-1}$. These closely comparable rates of decline tend to confirm

Figure 3.34 Piezometric head differential between the Khobar and Rus - Umm Er Radhuma 1997

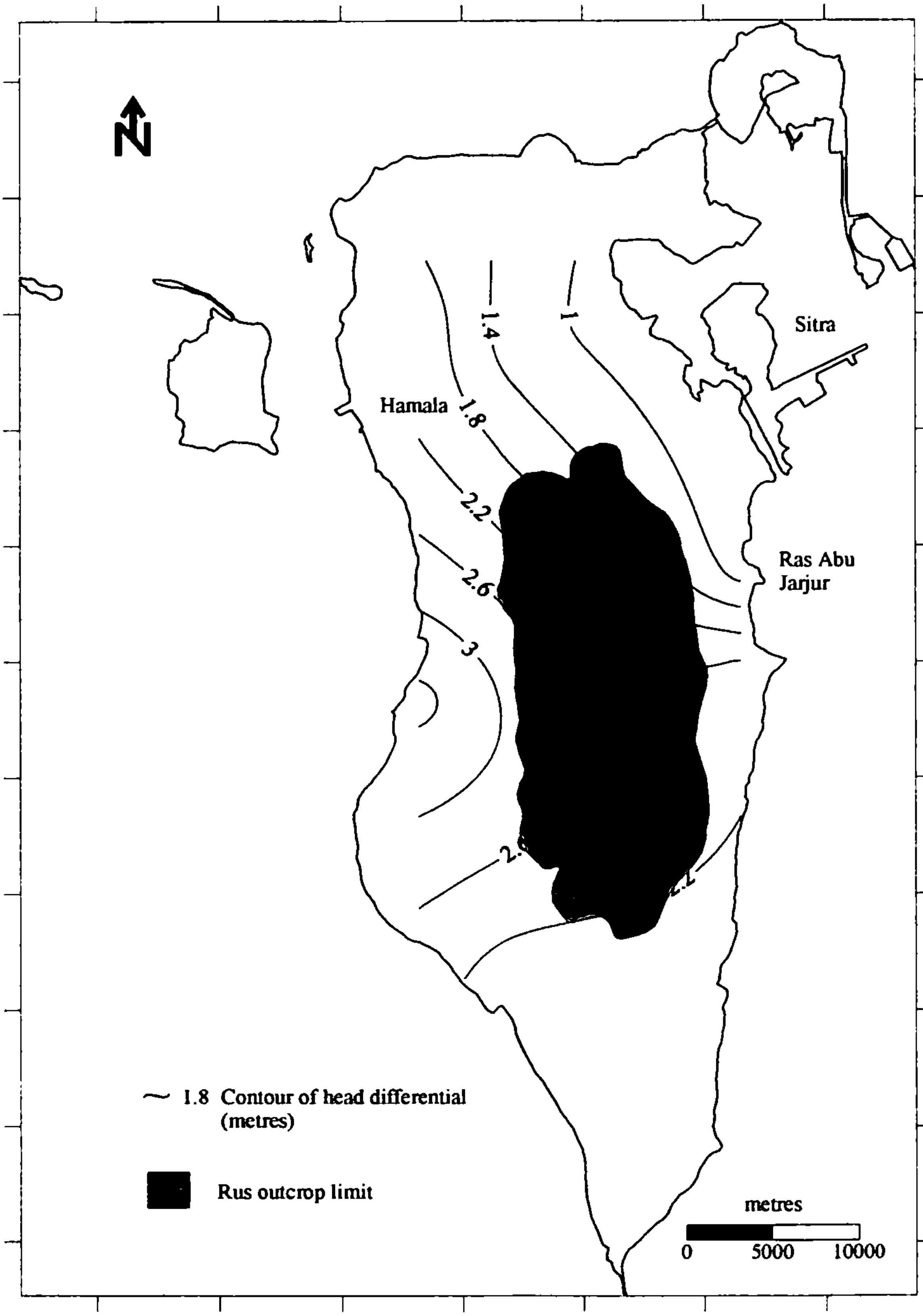
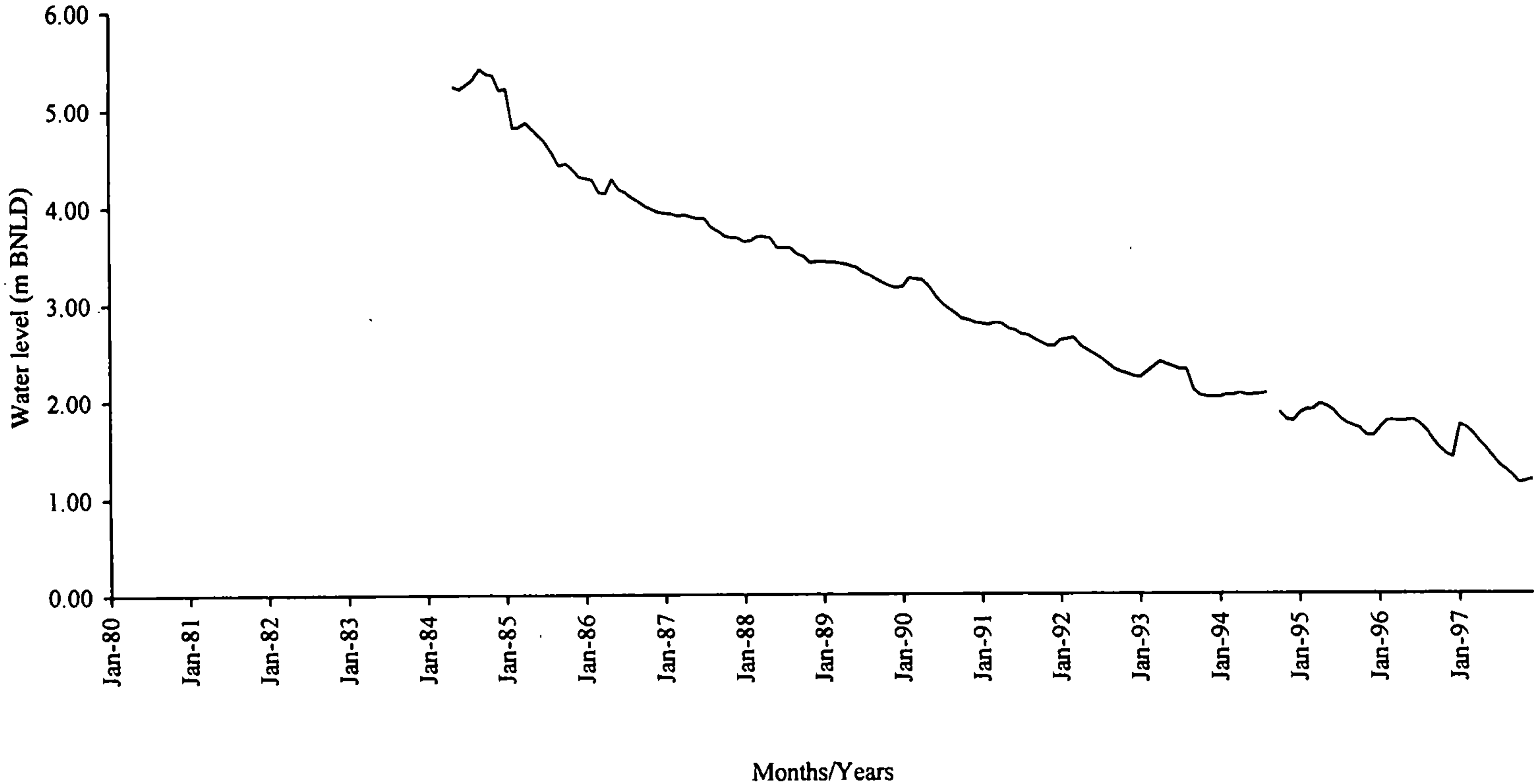


Figure 3.35 Well hydrograph showing the water level trend in the Rus - Umm Er Radhuma aquifer 1984 - 1997



the supposition made by Zubari (1994) that, with only minor exceptions, the drop in head in Aquifer 'C' is consistent, suggesting that the brackish water lens is gradually being depleted over the entire study area.

3.6 Recharge

Recharge to the underground aquifers in the study area occurs in several ways: present-day local recharge by direct infiltration of rainfall over the outcrop parts of the water-bearing formations, vertical transfer of water between the aquifers due to heads differential, particularly where aquitard materials are missing, and horizontal throughflow within the Regional Aquifer System. Modern recharge by irrigation return flow is also evident where topographic and stratigraphic conditions are appropriate.

In broad terms, present-day local recharge by infiltration from rainfall is precluded by scanty and high variability of rainfall, high evaporation rates, and outcrop configuration. Therefore, the major recharge forms are the throughflow from the Saudi Arabia mainland (outside the study area) and the transfer by vertical flow within the study area. Vertical transfer occurs by either upflows or downflows through the confining layers depending on the head differences between the aquifer systems. Throughflow case of recharge takes, as described by GDC (1980b) and illustrated in Figure 3.1, Section 3.1.1, a complex form as follows:

- infiltration of rainfall over the Umm Er Radhuma outcrop area in Al-Dahna desert in Saudi Arabia mainland.
- upward leakage of the lateral flow water from Umm Er Radhuma to the Dammam aquifers in the coastal belt of Saudi Arabia mainland and in

the offshore area between Bahrain and Saudi Arabia, through the non-anhydritic Rus (referred to as the Anhydrite Windows).

- throughflow from the Dammam aquifers in Saudi Arabia to the Dammam aquifers in Bahrain.

Isotopic age determination indicates that the age of the throughflow groundwater that reach the Dammam aquifers in the study area, as proven by GDC (1980b), is in the range of 6,000 to 22,000 years. The younger age is possibly a result of admixture with recent meteoric water, while the older ages may correspond with the two most recent pluvial periods in the region, 35 – 25,000 years BP and 8 – 5,000 years BP (Wright *et al.*, 1983).

Recharge Estimates

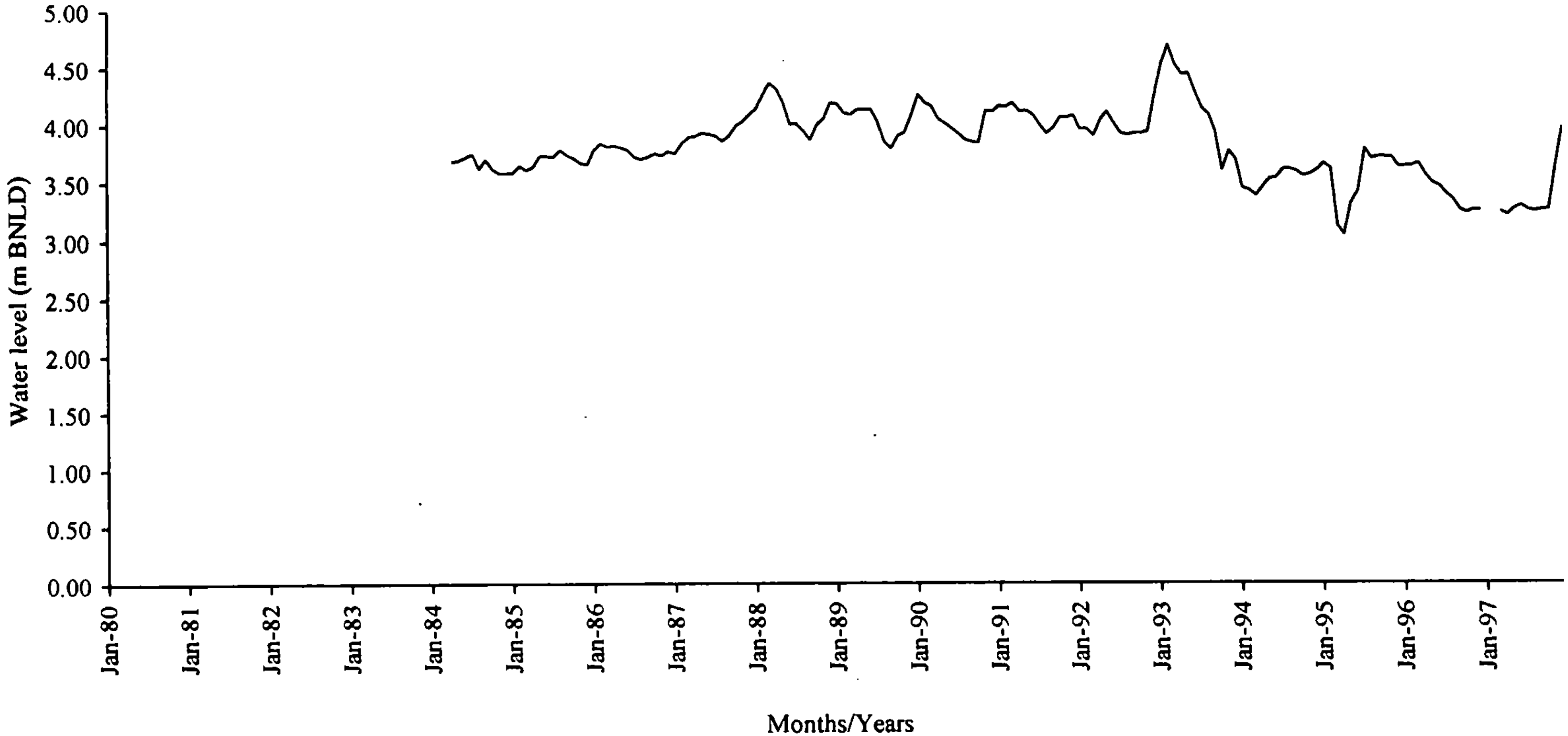
Modern local recharge is insignificant, and appears to be restricted to intensive rainfall in areas of appropriate topographic and hydrogeologic conditions. Recharge by infiltration around the core area is a modern recharge as confirmed by the isotopic studies (Italconsult, 1971; FAO, 1979; GDC, 1980b). A model was developed by GDC (1980b) to assess this case of recharge assuming a figure of 15 % of annual rainfall as recharge. The recharge estimates derived show a considerable variation from year to year, with a mean annual recharge of only 0.5 Mm^3 for the 15-year period analysed. As previously mentioned, this amount of recharge supplements the unconfined Rus aquifer with limited fresh perched water.

Present-day recharge to the unconfined Alat Limestone aquifer is taking place by a combination of direct infiltration from rainfall and return flow from irrigation around the intensively cultivated areas in Hamala, Janabiyah, and part of Saar. Al-Noaimi (1993) estimated the annual average recharge to the Alat from the water level fluctuations at about 0.18 Mm^3, based on assumed specific yield value of 0.15, an average water level rise of 0.085 m, and an aquifer total intake area of 14 km^2. This estimate is confirmed by the present study. The hydrograph in Figure 3.36 shows the water level behaviour of an Alat Limestone observation well located within the presumed recharge area where the aquifer crops out. The trend in this hydrograph exhibits a rather different pattern, which departs from the normal Dammam water level trends, and hence tends to strongly support the modern recharge supposition. Furthermore, from the author's field experience, anomalous salinity stratification and water level behaviour were observed at individual wells in the Janabiyah and Hamala areas where saline water is placed upon fresher water and Alat heads seem to be somewhat higher than those of the Khobar.

The outcrop configuration of the Khobar aquifer does not facilitate infiltration and recharge. Over such a steep backslope only a negligible amount of rainfall is likely to percolate to the aquifer; this amount is estimated by GDC (1980b) at about 0.1 $Mm^3 year^{-1}$. Replenishment to the Neogene aquifer by direct rainfall is possible where the aquifer outcrops and contains less claystone cover. However, because of the absence of quantitative hydrological data coupled with the scattered and isolated outcrop patterns, recharge to the Neogene could not be reliably estimated.

Recharge by vertical transfers via the overlying and underlying confining layers under the vertical hydraulic gradients does occur in the study area where favourable hydrogeologic conditions prevail. This recharge case is, however, difficult to estimate accurately as it involves substantial uncertainties. GDC (1980b) estimated the recharge to the Neogene by upflow from the Dammam aquifer system at about 0.5 Mm^3 $year^{-1}$. More recent estimates

Figure 3.36 Hydrograph showing the water level trend in well 1185 - Alat Limestone aquifer 1984 - 1997



on this recharge component were not available to the present investigation. Downflow recharge from the Neogene to the Dammam does not occur due to the positive head in favour of the latter, and if it does in certain cases, as postulated by GDC (1980b), it must be negligible.

Vertical leakage to the Dammam aquifers from the underlying Rus - Umm Er Radhuma is mainly controlled by the head difference between the two aquifer systems, together with the hydrogeologic behaviour of the Rus Formation. Hence, the amount of leakage flow varies considerably in time and space. GDC (1983a) estimated the recharge by vertical flow to the Dammam aquifers at 2 Mm^3 $year^{-1}$ during the presumed pre-development state, increased during the transient conditions to 18 Mm^3 $year^{-1}$ in 1956, and to 39 Mm^3 $year^{-1}$ in 1980. The later figure was used by GDC as input for their Khobar saline intrusion model. Clearly, such increases are ascribed to the increase in head difference between the two aquifer systems caused by the continuous decline in the Dammam water levels.

At present, as concluded by Zubari (1994), with the continuous lowering of the Aquifer 'C' heads due to the abstraction from Ras Abu-Jarjur wellfield, this leakage rate is expected to be declining. This is supported by the more recent head difference trend presented in Figure 3.34. GDC (1980b) predicted that the upward leakance to the Dammam from the Rus - Umm Er Radhuma aquifer in the year 2000 would be reduced by 25 Mm^3 from the 1980 estimate (i.e. to 14 Mm^3) because of the decrease in the head differential. This figure is regarded acceptable on the basis of the current abstraction level from the Rus - Umm Er Radhuma, and the continuous decrease in head differential between the two aquifers as demonstrated by the contour difference in Figure 3.34.

Throughflow reaching the study area from Saudi Arabia mainland was estimated by GDC (1980b) at between 83 - 90 Mm^3 $year^{-1}$, on the assumption that this amount represents the total outflows from the natural springs when the system was in steady state condition. Al-Noaimi (1993) reconsidered this estimate using a regression analysis approach that related well abstraction from the Dammam aquifers, average decline in spring discharge, and the drawdown rates over the period 1924 - 2000, assuming that the abstraction from the Dammam aquifers would continue at the same rate up to the year 2000, and the lowering in the Dammam water levels has only started between 1942 - 1950. The analysis indicated that the Dammam Aquifer System in Bahrain receives an annual recharge of between 106 – 116 Mm^3. An average throughflow figure of 112 Mm^3 $year^{-1}$ was used in estimating the groundwater budget for the Dammam - Neogene for the year 1990.

As stated earlier, the Rus - Umm Er Radhuma aquifer in the study area forms a lens of limited lateral extent and underlain everywhere by highly saline brine (GDC, 1983b). Lateral inflow to the Rus - Umm Er Radhuma aquifer across the western boundary with the regional system does not exist, and if it does is insignificant, hence, apart from the aforementioned localised infiltration of rainfall within the interior basin area, this lens is virtually non-renewable (GDC, 1980b; 1983b).

BAPCO dumps oily water produced as part of its oil field operations into the Rus - Umm Er Radhuma aquifer within the core area. This artificial recharge practice started in 1960 with small quantities, and increased progressively with the ageing of the oil field (Zubari, 1994). The oil-associated water is injected into waste-disposal wells after being separated from the crude oil at tank battery facilities. The annual rate of injection is about 7 Mm^3 $year^{-1}$ (total of about 280 Mm^3 from 1963 to 2000), with an average TDS concentration of around 8,000 mg l^{-1}, and oil content of 230 mg l^{-1} (S. Polinar, Water Resources Directorate, personal communication).

In addition, the water authority in Bahrain operates a number of small artificial recharge projects. These projects were designed to recharge both the Dammam and Rus - Umm Er Radhuma aquifer systems, and were constructed at specifically selected sites where hydrogeological conditions are most favourable. The replenishment takes place by means of induced infiltration through shallow wells. Even though, these recharge facilities are yet to be quantitatively assessed, crude estimates suggest an annual recharge of 0.3 Mm^3 and 0.2 Mm^3 to the Dammam and Rus - Umm Er Radhuma, respectively.

In view of the above discussion, it can be concluded that the annual recharge to the Dammam aquifer system in the study area is about 126.6 Mm^3, whilst the Rus - Umm Er Radhuma aquifer receives about 7.7 Mm^3 $year^{-1}$. Table 3.9 presents the estimated recharge to these aquifer systems for each recharge case.

3.7 Discharge

Traditionally, discharge in the study area occurs in two forms: (i) natural discharge, which includes discharge from sabkha surfaces, evaporation from shallow water tables, and discharge from natural springs; and (ii) artificial discharge by abstraction from artesian and shallow hand dug wells. In addition, up to the end of 1960s, another form of discharge was occurring by free flow from artesian wells in many parts of the study area, including the marginal islands. With the continuous decline in the Dammam aquifer heads, however, this form of discharge had almost completely ceased.

Table 3.9 Recharge estimates to the aquifer systems in the study area in million cubic meters

Recharge case	Neogene	Dammam Aquifer System			Rus - Umm Er Radhuma Aquifer System
		Alat Limestone		Khobar	
Local recharge by infiltration from rainfall and irrigation recyching	--	0.18		0.1	0.5
Local recharge by vertical transfer	0.5		14 (2)		—
Regional recharge by throughflow from Saudi Arabia mainland	—		112		—
Artificial recharge by induced infiltration and well injections	—			0.3	7(0.2)
Total recharge	0.5		126.6		7.7

Notes: [1] (–) indicates no estimate.
[2] Local recharge by vertical infiltration is taken as 25 Mm^3 reduction from the 1980 estimate based on GDC model prediction.
[3] (__) indicates no recharge.
[4] Bracketed figure is induced infiltration.
[5] Rounding to the nearest decimal may result in total not equal 100%.
[6] Artificial recharge by injection represents average since 1960; the 1998 figuer was 13.93 Mm^3.

3.7.1 Natural Discharge

Sabkha Discharge

Sabkha is an Arabic term commonly applied to the coastal salt flats or salt marshes formed under arid to semi-arid conditions, and are inundated periodically by rainwater or by high tides; their level is dictated dominantly by the local level of groundwater table (Encyclopaedia Britannica, 1992b; Kinsman, 1969). During dry seasons, the sabkha surface is characterised by encrusted evaporite-salts and aeolian deposits. Discharge from sabkha surfaces is caused by a positive vertical flow from the underlying aquifer, and is mainly effected by water level and salinity in the aquifer, and thickness and salinity within the sabkha surface. For example, evaporation rates decrease as the salt content increases and fall considerably where a continuous surface layer of salt forms a physical barrier to escaping water by capillary action (GDC, 1980b).

GDC (1980b) has calculated the total evaporation losses from sabkha for both Bahrain and the coastal belt of Saudi Arabia mainland at about 386 Mm^3 $year^{-1}$, using the energy balance method. This figure was computed based on the assumption that sabkha evaporation takes place at about 22 % of the total evaporation rate (1,702 mm), and occurring on about 80 % of the sabkha surface. It was assumed that evaporation of groundwater from sabkha could be taken as a measured proportion of the total potential evaporation.

In Bahrain, the two major coastal sabkhas are the southwestern sabkha and the southern sabkha. They occupy a total area of approximately 90 km^2. Mean annual evaporation, as stated in Chapter Two page 102, is about 2,099 mm. Therefore, applying the same approach, potential evaporation of about 462 mm on 72 km^2 of sabkha surface results in evaporation from sabkha totaling about 33 $Mm^3 year^{-1}$. GDC (1980b), however, assumed that sabkha discharge remains constant over the first 0.3 m of head decline and then decreases linearly to zero over the subsequent 4 m of head decline. The head decline in the Khobar aquifer over the sabkhas' area since the steady state condition is estimated at about 2.7 m (see Figures 3.27 and 3.28). This would put the present sabkha discharge at approximately 11 Mm^3. It must be noted, however, that the coastal sabkhas south of Sitra Island and along the Ras Hayyan coastline have been excluded from this estimates due to the absence of data.

Evaporation from shallow water tables

The evaporation from shallow water tables occurs primarily in the cultivated areas through transpiration by vegetation cover. According to GDC (1980b), this discharge component is a measure of consumptive use from the Neogene outcrop areas, with palm trees cultivation. For their model calibration, they accepted a water consumptive rate over these areas of 1,000 mm $year^{-1}$, and by assuming a gross cultivated area of 17.5 km^2 in 1979, they estimated the evaporation from shallow water tables at about 17.5 Mm^3. The same procedure is adopted here to calculate this component for the year 1997. Presently (2000), the areas under date palms occupy about 8.2 km^2, implying that water discharged through evapotranspiration from shallow water tables is nearly 8.2 $Mm^3 year^{-1}$.

Spring Discharges

Most of the land springs in the study area are concentrated around the eastern area, whilst the majority of the submarine springs occur in an intertidal zone off the northeastern coast of Bahrain main island. Most of the Bahrain land springs are believed to emanate from the Alat Limestone aquifer; although Hamilton (1965) claimed that some of them have production capacities large enough to suggest a Khobar source. Kathira spring in the east coast probably originates from the Rus aquifer (Steineke, 1942) or a combination of Khobar and Rus aquifers (Gulmon, 1941). The submarine springs mostly originate from shallow-seated collapse structures in the Neogene aquifer.

The discharge history of the natural springs in the study area has been fairly well documented since 1924. However, some of the earlier estimates are considered inaccurate, and were adjusted and re-estimated at various stages (see the discussion in Chapter One, page 37, for full details of these adjustments; refer also to Table 6.4 of Chapter Six, which illustrates the history of spring discharges). The first row of Table 3.10 summarises the total flow from both land and offshore springs from 1924 to 2000. It shows that the discharge from springs declined from 29 Mm^3 in 1971 to 5 Mm^3 in 1990, representing a decline of almost 83%. It should be noted that the 1990 figure is an estimate based on the analysis of long-term water level decline against spring discharges and abstraction from Dammam wells (Al-Noaimi, 1993). The same analysis indicated that springs would cease to flow by the year 1995. Fieldwork during the present investigation (1997), however, revealed that some of the land springs were still flowing and their discharge was estimated at about 1.2 Mm^3. The corresponding submarine springs flow is estimated at about 0.6 Mm^3. The total spring discharges for 2000 can be crudely estimated at about 1.2 Mm^3, shared between the land and offshore springs at 0.4 Mm^3 and 0.8 Mm^3, respectively (see Table 6.4 of Chapter Six).

3.7.2 Well Abstraction

The first water well was drilled in the study area in 1925. Since then the number of wells drilled into the Dammam and Neogene aquifers has steadily increased to 1,307 wells in

Table 3.10 Historical data on groundwater withdrawal, spring discharges and number of wells drilled into the Dammam/Neogene aquifers 1924 – 2000

Description	1924	1952	1966	1971	1979	1987	1990	1997	2000
Discharge from natural springs	83.0	54.8	37.6	29.0	14.7	7.1	5.0	1.8	1.2
Number of wells	0.0	280.0	780.0	980.0	1307.0	1803.0	1890.0	2171.0	2198.0
Abstraction from Dammam/Neogene	0.0	63.2	113.6	125.1	138.1	179.9	187.3	250.9	218.8
Abstraction from Rus - Umm Er Radhuma	0.0	2.0	2.0	2.0	9.3	33.3	32.0	36.9	44.6

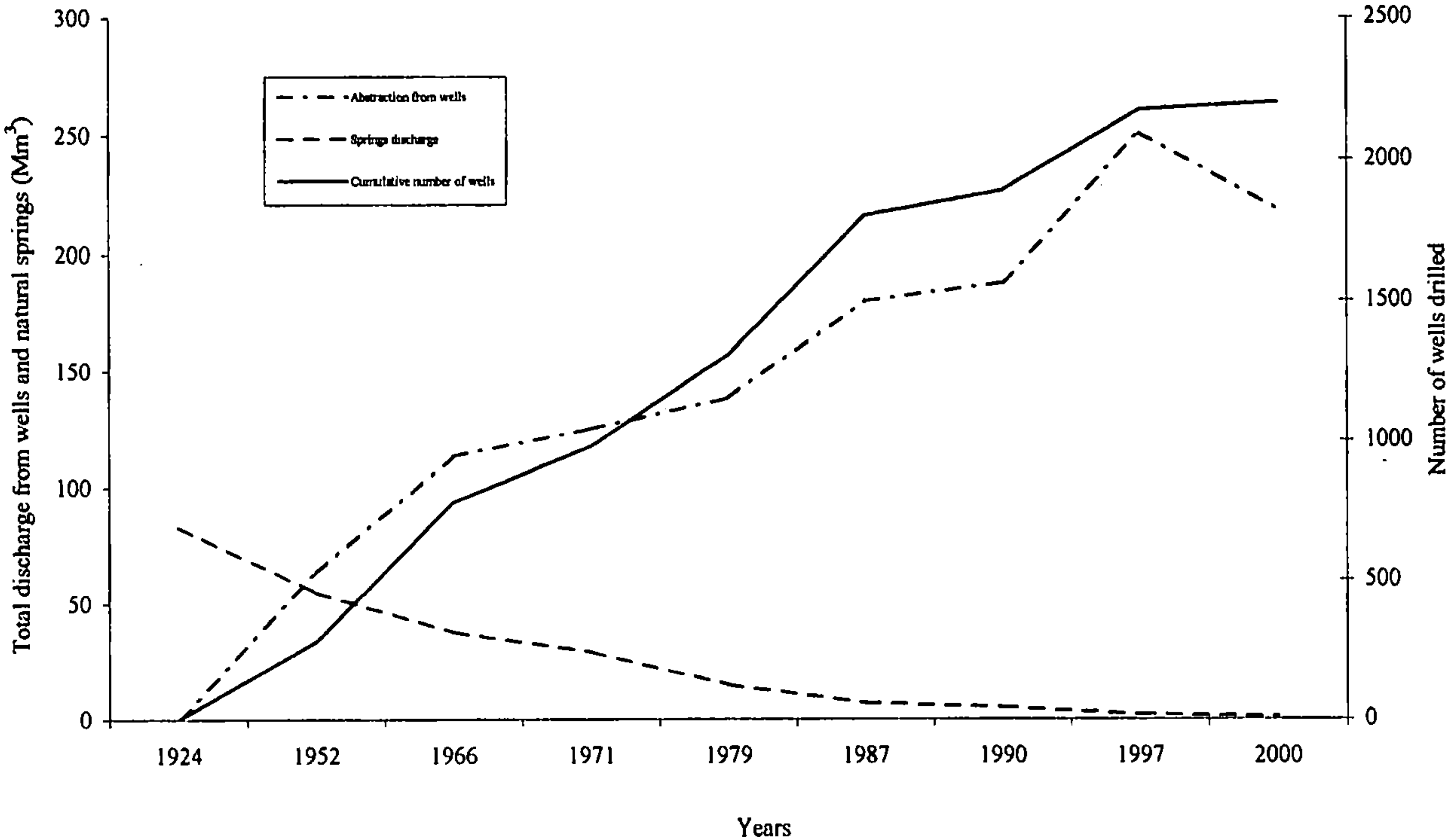
SOURCE: Updated from Al-Noaimi 1993.
Note: Discharge and abstraction data are in million cubic metres.

1979, and reached a figure of 2,198 wells by the end of year 2000. This has been accompanied by a marked increase in groundwater abstraction, and, as noted above, a progressive decline in spring flows. Table 3.10 also presents historical data on number of wells drilled into the Dammam and Neogene aquifers, and total groundwater abstraction from both Dammam and Rus - Umm Er Radhuma aquifer systems, while the relation between the first two sets of data and springs flows is displayed diagrammatically in Figure 3.37.

Total withdrawal from the Dammam and Neogene aquifers increased from 63.2 Mm^3 in 1952 to 113.6 Mm^3 in 1966, and to 125.1 Mm^3 in 1971. An estimate by GDC in 1979 put the groundwater abstraction from these aquifers at 138.1 Mm^3. In 1987, the total groundwater withdrawal was 179.9 Mm^3, and rose to 187.3 Mm^3 in 1990. More groundwater continued to be withdrawn from this aquifer system, raising the abstraction level to about 250.9 Mm^3 in 1997. A more recent estimate for the year 2000 indicates decrease in abstraction by around 13% to about 218.8 Mm^3 owing primarily to the decrease in municipal withdrawal from 65.16 Mm^3 in 1997 to 52.73 Mm^3 in 2000, in response to the increase in desalination capacity introduced by the third quarter of year 2000.

The table also shows that the Rus - Umm Er Radhuma aquifer abstraction remained unchanged at 2 Mm^3 from 1952 to 1971, and increased to 9.3 Mm^3 only in 1979. By 1987, following the major abstraction from Ras Abu-Jarjur wellfield, which was started in 1984, total withdrawal from this aquifer system drastically increased to reach about 33.3 Mm^3. Groundwater pumpage data reported by the WRD showed abstraction slightly reduced to about 32 Mm^3 in 1990, but again increased to 39.1 Mm^3 in 1997. At present

Figure 3.37 The relation between total discharge from wells, discharge from springs and number of wells drilled 1924 - 2000



(2000) groundwater withdrawal from this aquifer is estimated at 44.6 Mm^3.

3.8 Groundwater Budgets

The groundwater budget is simply the balance between the total inflows to a given aquifer system and total outflows from this system. The relationship between these components may be expressed by the traditional water budget equation:

Inflows (recharge) – Outflows (discharge) = Change in Storage

The change in storage is negative (deficit) when the total outflow exceeds the total inflow. Conversely, a positive change in storage (surplus) takes place when the situation is reversed. This relation was applied to calculate the groundwater budget of the Dammam - Neogene aquifer system. Data on recharge and discharge estimates discussed earlier and summarised in Tables 3.9 and 3.10 have allowed preparation of a generalised groundwater budget for this aquifer for the year 2000 as presented in Table 3.11. Although, it contains some poor estimates, especially with regard to recharge by vertical leakage and discharges from sabkha surface and shallow water tables, the analysis of this groundwater budget seems reasonable, and indicates a deficit of about 112.6 Mm^3. Practically, however, the abstraction data show that groundwater has been taken from the aquifer storage since about 1945.

Al-Ghamdi (1999) has calculated a water budget for the Rus - Umm Er Radhuma aquifer for the period 1965 - 1998 by assuming that the abstraction from Ras Abu-Jarjur wellfield and the injection of the oily water at Bahrain oilfield are the major discharge and recharge components. The other sources were considered insignificant. He found that water so far

Table 3.11 A generalised groundwater budget for the Dammam-Neogene aquifers 2000

Recharge/discharge components		Recharge/discharge rates (million cubic metres)
Inflows		
Recharge by throughflow from mainland		112
Recharge by vertical transfer		14
Local recharge by infiltration from rainfall		0.28
Artificial recharge by induced infiltration		0.30
	Total inflows	126.6 (rounded)
Outflows		
Abstraction from wells		218.8
Discharge from natural springs		1.2
Discharge from sabkha surface		11.0
Evaporation from shallow water tables		8.2
	Total outflows	239.2
Change in storage: (Inflows – Outflows)		-112.6

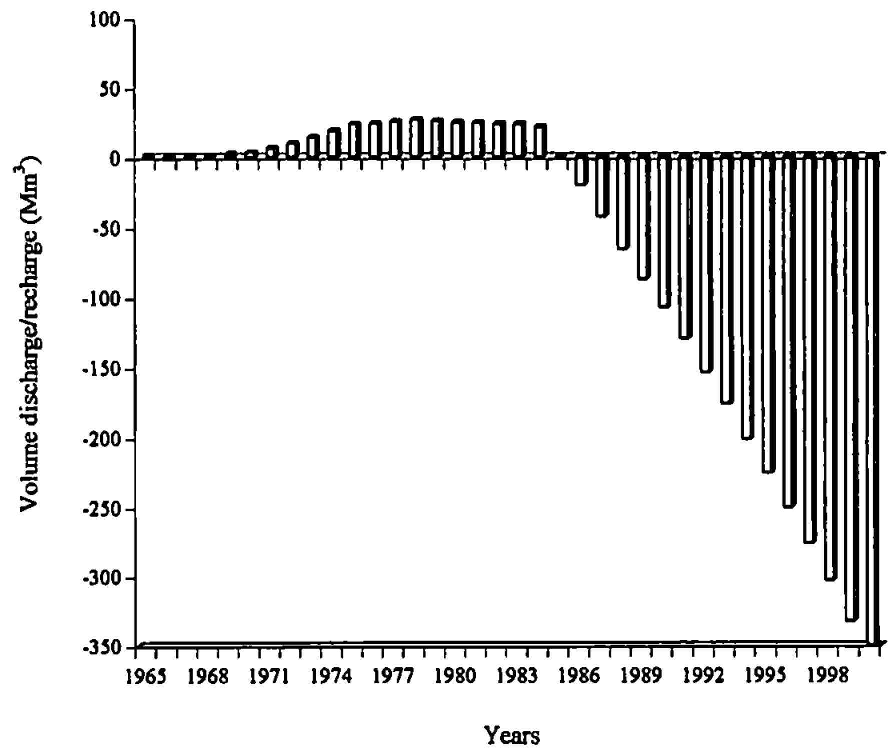
withdrawn from the aquifer represents only 0.68% of the brackish water volume in storage based on a minimum reserve estimate of about 28,000 Mm^3.

In this study, modern recharge to the aquifer at Bahrain core and discharge from the aquifer for industry and non-productive agriculture purposes were considered important recharge and discharge components and, together with the components employed by Al-Ghamdi, were used to estimate the Rus - Umm Er Radhuma aquifer water budget. Only the leakage flow to the Dammam aquifer is excluded from this estimate. This elimination is justifiable given the lack of reliable annual estimates on this form of outflow. The estimated groundwater budget for the Rus - Umm Er Radhuma aquifer for the period 1965 – 2000 is shown in Figure 3.38.

The results indicate that the total cumulative volume of groundwater abstracted from the aquifer up to the year 2000 was about 687.33 Mm^3, while that entering the aquifer by recharge was around 325.21 Mm^3, indicating a deficit of 362.12 Mm^3. Owing to the relatively huge quantity of water in storage, this amount represents only 1.3 % of the available minimum reserve. It should be emphasised, however, that the above water budget analysis indicates that the deficit in the Aquifer 'C' brackish water lens started about 1986 (1994 in Al-Ghamdi's calculations), confirming the gradual depletion of this brackish water lens.

Year	Cumulative injection of oily water	Cumulative recharge at Bahrain core	Cumulative abstraction from Ras Abu-Jarjur	Cumulative abstraction for Industry and non-productive agriculture	Net discharge/recharge volume
1965	0.72	0.5	0	2.0	-0.75
1966	1.95	1.0	0	4.0	-1.05
1967	4.00	1.5	0	6.0	-0.5
1968	6.72	2.0	0	8.0	0.72
1969	9.64	2.5	0	10.0	2.14
1970	12.47	3.0	0	12.0	3.47
1971	17.00	3.5	0	14.0	6.50
1972	22.14	4.0	0	16.0	10.14
1973	27.71	4.5	0	18.0	14.21
1974	33.97	5.0	0	20.0	18.97
1975	40.33	5.5	0	22.0	23.83
1976	47.20	6.0	0	29.0	24.20
1977	55.01	6.5	0	36.0	25.51
1978	62.89	7.0	0	43.0	26.89
1979	70.91	7.5	0	52.30	26.11
1980	78.44	8.0	0	61.60	24.84
1981	87.00	8.5	0	70.90	24.60
1982	95.76	9.0	0	80.90	23.88
1983	105.35	9.5	0	90.90	23.95
1984	115.37	10.0	2.9	100.90	21.57
1985	125.90	10.5	28.47	108.02	-0.009
1986	136.64	11.0	52.97	114.62	-19.95
1987	146.97	11.5	76.68	124.12	-42.33
1988	157.49	12.0	99.29	135.62	-65.42
1989	167.36	12.5	120.90	145.72	-86.76
1990	178.55	13.0	143.95	154.72	-107.12
1991	189.64	13.5	169.56	163.22	-129.64
1992	201.59	14.0	196.65	172.82	-153.88
1993	213.90	14.5	221.68	182.42	-175.70
1994	226.53	15.0	250.02	192.12	-201.14
1995	239.49	15.5	276.94	203.62	-225.57
1996	252.77	16.0	303.53	215.62	-250.38
1997	266.83	16.5	331.61	227.82	-276.10
1998	280.29	17.0	359.14	241.32	-303.17
1999	293.75	17.5	389.62	253.72	-332.09
2000	307.21	18.0	420.61	266.72	-362.12

Figure 3.38 A generalised groundwater budget for the Rus - Umm Er Radhuma aquifer 1965 - 2000



CHAPTER FOUR
GROUNDWATER CHEMISTRY

Regionally, the study area occupies a unique position within the Eastern Arabian Aquifer System since it is one of the most easterly known discharge areas of that system (GDC, 1980b), which has a direct bearing on the hydrochemistry and groundwater salinity distribution. Groundwater in the Dammam aquifer system increases in the direction of the regional groundwater flow, although this simple picture is complicated by locally high salinity values in the north-central part, attributed to the upward migration of saline water from the deeper Rus - Umm Er Radhuma aquifer to the unconfined Khobar aquifer. Groundwater in the Rus - Umm Er Radhuma aquifer system seldom follows this regional flow pattern (GDC, 1980b).

The groundwater chemistry in the study area has been investigated in terms of concentrations of major and minor dissolved constituents, areal distribution of total dissolved solids, chemical classification and characterisation, ionic ratios, and equilibrium speciation. The temporal changes in dissolved solids concentration of groundwater from the Khobar aquifer for the period 1991/92 – 1999/2000 have also been investigated by means of a contour difference map. In addition, water from Bahrain land springs was evaluated in terms of its chemical and bacteriological quality.

4.1 Sampling and Analysis

Water samples from some 286 wells of the Dammam aquifers were collected in three stages, firstly during the periods from March - September 1997, secondly from February to April 1998, and thirdly during the period from September 1999 to October 2000. Out of these samples, 262 were from the Khobar aquifer and 24 samples from the Alat Limestone aquifer. Prior to sampling, each well was pumped for at least three minutes in order to obtain representative samples. Because some of the Dammam samples were analysed in another laboratory, a random selection of nine samples was subjected to a duplicate analysis at the two laboratories as a cross-check for analytical reliability. The obtained results (Table 4.1) show that there is no significant difference between the mean values of the same groups of samples, with ($\rho > 0.05$) at 95% level of confidence.

Table 4.1 TDS results of duplicate analysis of a random selection of nine samples

Well no.	Location	Total dissolved solids concentration in mg l^{-1}	
		Magnum Laboratory	WRD
6/86	Sadad	5787	5599
1108	Hamala	2295	2230
6/47	Sadad	9004	9056
1623	Manama	2745	2714
1300	Al-Areen	7963	7469
7/19	Wasmiyah	6044	6413
7/32	Zallaq	5521	5878
6/23	Zallaq	3768	3900
1266	Al-Jazair	12338	12256
Mean value		6163	6168

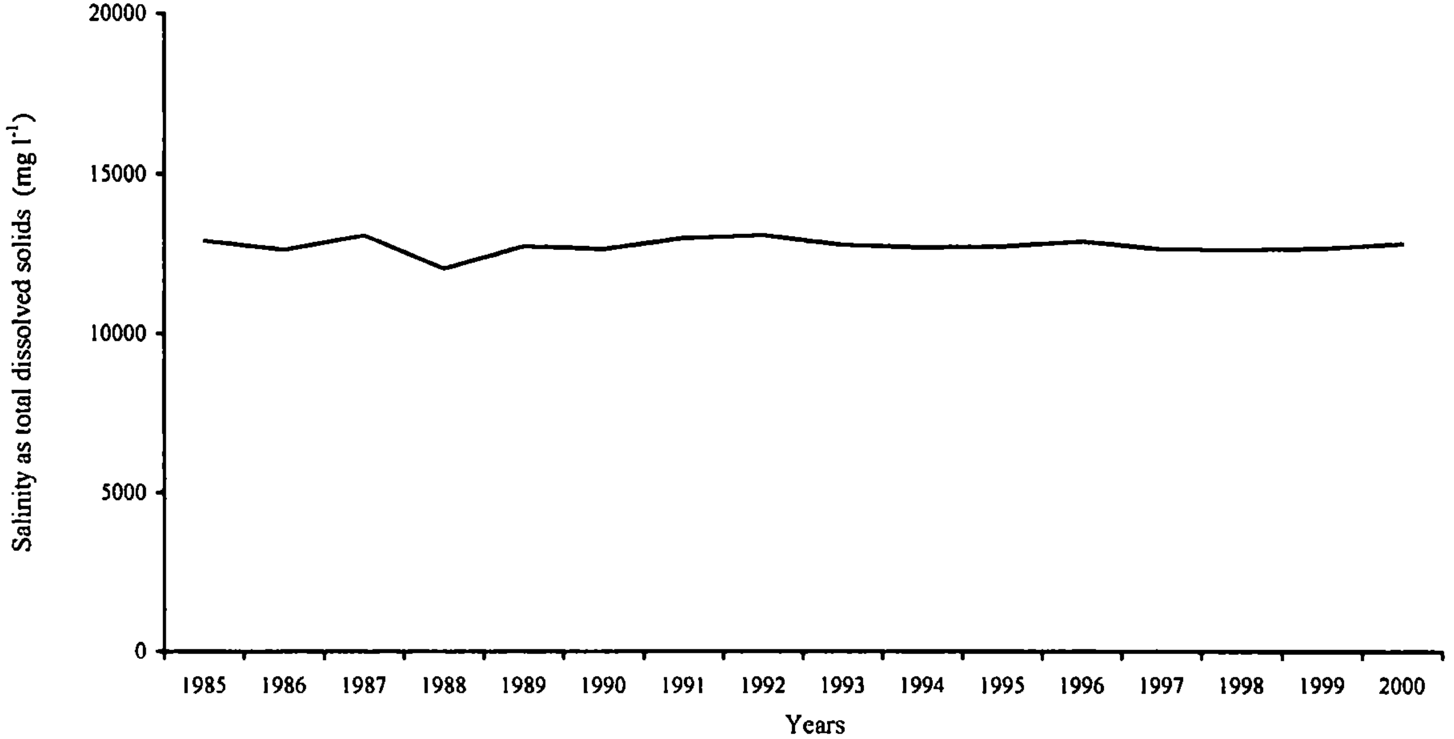
P value 0.952

The sampling points of the Dammam aquifers are shown in Figure C-1 of Appendix C. Water samples were also obtained from 11 land springs across the study area. Their locations are given in Appendix C, Figure C-2. These springs were re-sampled at a later stage for bacteriological determination. Owing to their bad condition, most of the samples collected from the natural springs were grabbed samples; only a few were from minor free flow.

Chemical analyses of about 63 samples from the Rus - Umm Er Radhuma aquifer, collected between 1983 to 2000, were compiled from several unpublished data files, and were used to investigate the chemical composition and salinity distribution in this aquifer. The locations of the wells from which data were obtained are shown by Figure C-3, Appendix C. It is assumed that the salinity pattern and ionic composition represented by these analyses also delineate the current salinity trend in the aquifer. This assumption is reasonable enough based on the results of the modelling studies (GDC, 1983a; Zubari, 1994), and is also be well supported by the long-term salinity observation at the Ras Abu-Jarjur Wellfield. Figure 4.1 shows the average total dissolved solids concentration at this wellfield over the last 16 years (1985 – 2000). From the figure, it is evident that no appreciable salinity changes have occurred since the onset of large-scale abstraction from the wellfield.

Out of the Dammam samples, 164 of the Khobar, and 12 of the Alat samples were analysed for electrical conductivity (EC), TDS, total hardness as $CaCO_3$, total alkalinity as $CaCO_3$, pH, temperature, major ions: Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-, secondary constituents: F^-, B, NO_3-N, NO_2-N, NH_3-N, PO_4-P, Fe (total iron), Al^{3+}, and heavy metals: Cu, Zn, Ni, Pb, Cd, Mn, Co, Cr. Twenty-five of the Khobar samples were analysed for the same parameters excluding the heavy metals, while the remaining 73 samples of the Khobar and 12 of the Alat were analysed only for the general parameters, including EC, TDS, total hardness, total alkalinity, pH, and the major ions. Additionally, EC and TDS results of four Alat wells were obtained from the WRD data

Figure 4.1 Salinity trend at Ras Abu-Jarjur Wellfield 1985 - 2000



files to complete the areal salinity distribution in the aquifer. Nine of the natural springs samples received full chemical analysis, including secondary constituents and heavy metals analysis, whilst two samples were analysed only for EC, TDS, total hardness, total alkalinity, pH, and the major ions. In relation to the bacteriological analysis, nine samples were analysed with respect to total *coliforms* and *Escherichia. Coli (E. Coli)*.

The analytical methods used for analysing the Dammam and natural springs water samples are listed in Table 4.2. The membrane filtration technique was used to determine the bacteriological content of the natural springs. Standard methods (APHA, 1985) were used for the determination of the chemical composition of the Rus - Umm Er Radhuma aquifer water samples. The pH and EC were measured in the laboratory using standard pH and EC meters. Concentrations of Cl^-, HCO_3^-, and CO_3^- were determined using volumetric titration method. A gravimetric method was used to measure SO_4^{2-}, whilst Ca^{2+} and Mg^{2+} were measured volumetrically (EDTA method). Na^+ and K^+ were determined by flame photometry.

4.2 The Dammam Aquifer System

The chemical analysis results of the Alat Limestone samples can be found in Appendix C, Table C-1. The table shows that the pH averaged 7.2, indicating slightly alkaline groundwater. Groundwater in the Alat is very hard with hardness as $CaCO_3$ ranging from 790 mg l^{-1} to 3,260 mg l^{-1}. TDS concentrations ranged between 2,266 and 13,796 mg l^{-1}. However, this trend is biased because of the anomalously high concentration of total dissolved solids (13,796 mg l^{-1}) in well 1602 located in Al-Akur area slightly inland from Sitra coast. Although, this area has an established history of salinity degradation experienced in some irrigation hand-dug wells completed into the Neogene/Alat, such an

Table 4.2 Analytical methods used to analyse water samples from the Dammam aquifers and natural springs

Parameter	Method of analysis	Detection limit
pH and EC	Portable pH and EC meters with standard temperature compensation control	1.0 pH unit and 1.0 $\mu S\ cm^{-1}$
Temperature	Calibrated mercury thermometer	---
TDS	Summation of cations and anions	5.0
Total hardness as $CaCO_3$	EDTA titration method with Eriochrome – T indicator	< 1.0
Total alkalinity as $CaCO_3$	Burette titration method with HCl and methylorange indicators	< 5.0
Ca and Mg	EDTA titration method with solochrme dark blue indicator	0.003 and 0.0005
Na and K	Flame photometric method	0.01
Cl	Argentometric method with potassium chromate as indicator	< 0.001
SO_4	Turbidimetric method	< 0.001
CO_3 and HCO_3	Calculated from alkalinity titration using standard formulas	< 0.001
F	Spectrophotometer – Spands method with zirconium dye indicator	< 0.001
B	Spectrophotometer – carmine method with carmic acid indicator	< 0.001
NO_3- N	Spectrophotometer – cadmium reduction method with sulphanic acid indicator	< 0.001
NO_2-N and NH_3-N	Spectrophotometer – diazotization and Nessler methods, respectively.	< 0.001
PO_4-P, Fe and Al	Spectrophotometer method with ascorbic acid, a standard phenanthrotine solution, and aluminon reagent indicators, respectively.	< 0.001
Heavy metals	Spectrophotometric method using various detection techniques	0.002 – 0.01

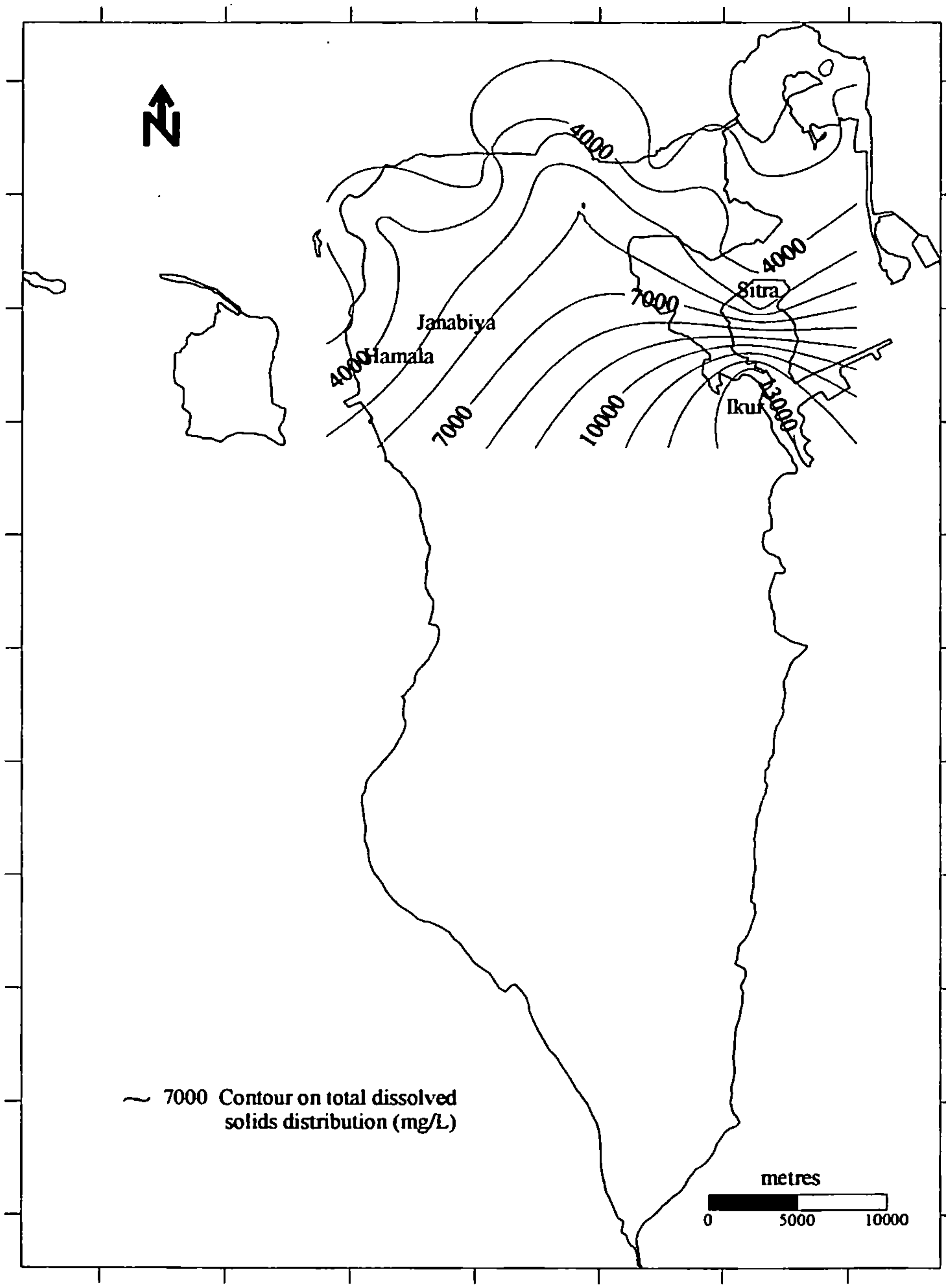
All the detection limit values are in mg l^{-1}, unless otherwise stated.

elevated TDS level seems very high and may be related to malfunction during well construction. With the omission of this well, the TDS range is from 2,266 to 6,017 mg l^{-1}. Calcium levels fall in the range from164 to 601 mg l^{-1}, and magnesium varies from 49 to 476 mg l^{-1}. Sodium is the most abundant cation in the Alat Limestone aquifer, with concentration varying from 456 to 3,770 mg l^{-1}. The mean value of potassium is 38 mg l^{-1}, with a concentration fluctuating between 20 to 155 mg l^{-1}.

Among the anions, chloride is the most dominant ranging from 798 to 7,108 mg l^{-1}, and it correlates directly with the sodium concentration. The second most dominant anion is the sulphate with concentrations varying from 475 to 1,479 mg l^{-1}, followed by the bicarbonate at between 125 and 297 mg l^{-1}. Carbonates were not present in all the water samples examined. Fluoride and boron concentrations range from 0.8 – 1.34 mg l^{-1}, and from 0.4 – 0.6 mg l^{-1}, respectively. Nitrate-nitrogen varies from 2.8 to 6.0 mg l^{-1}. Total iron concentration was found to vary from 0.07 to 1.65 mg l^{-1}. Ammonia, phosphorous, aluminum, cobalt, copper, zinc, nickel, and chromium were all present in concentrations of less than 0.01 mg l^{-1}. The levels of nitrite-nitrogen, lead, cadmium, and manganese were below 0.001 mg l^{-1}, with some samples recording nil nitrite-nitrogen content.

Little hydrochemical information now exists on the Alat Limestone aquifer, but older data show Alat salinities regionally distributed as those of the Khobar (GDC, 1980b). This possibly holds true up to present, although Alat wells seem to be less affected by some of the recent forms of contamination. Only a few water wells are at present producing from the Alat Limestone aquifer alone, of which many are sampled as part of this study. The general pattern of total dissolved solids distribution in the Alat aquifer is shown in Figure 4.2. As expected, this pattern is inversely related to the regional groundwater flow

Figure 4.2 Distribution of total dissolved solids in the Alat Limestone Aquifer 1999/00



regime, in which salinity increases along the NW-SE flow path.

Groundwater with TDS of less than 3,000 mg l^{-1} is found in the northwestern and northeastern coasts. The contour pattern in the northeastern areas clearly reflects the preferential flow path referred to earlier. The total dissolved solids concentrations in the Alat Limestone aquifer significantly increase down gradient towards Sitra and the remainder of the eastern villages. As previously indicated, higher concentrations as a result of localised pumpage generally are found near Al-Akur village. Although contours of more than 6,500 mg l^{-1} are seen passing over areas where the Alat is at surface (Hamala and Janabiyah), localised high salinities caused by irrigation return flow are not clearly depicted in this map, though well documented with field and water level evidence. The unconfined Alat in these areas is of limited productivity, and wells are usually opened in both Dammam aquifers or the Khobar only; therefore recent chemical analyses of Alat-only wells are unavailable.

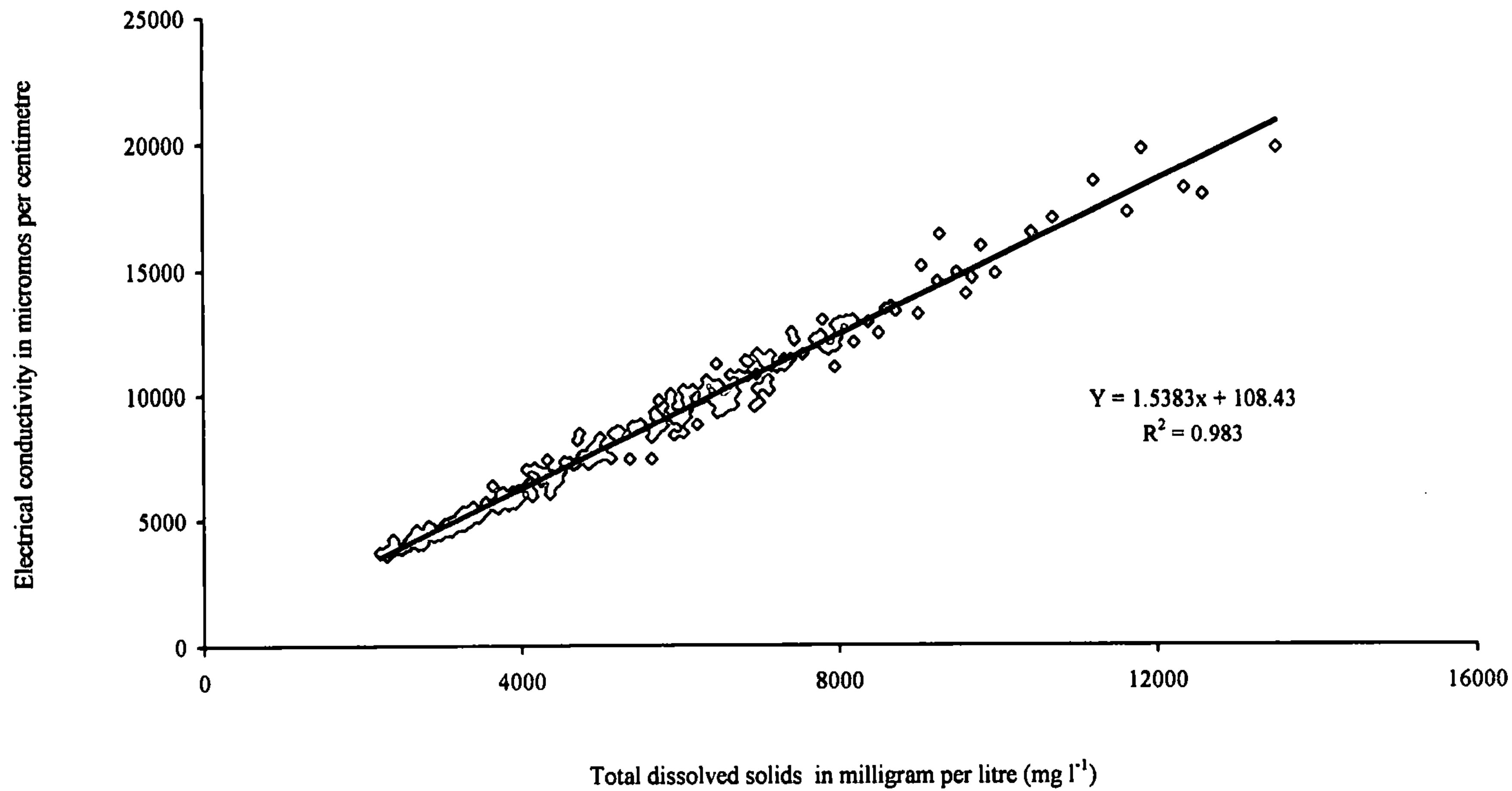
The chemical analysis results of groundwater from the Khobar aquifer are tabulated in Table C-2 of Appendix C. The table indicates that the Khobar groundwater is a mildly alkaline, having a pH average value of 7.1. Redox potential (Eh) was not measured during this investigation, but a previous study (GDC, 1980b) shows that Khobar water is positive with Eh values ranging from +35 to +227 millivolts (mV), suggesting mildly oxidising conditions. Temperature ranges from 26 °C to 29 °C, and averages 27 °C. The average total hardness as $CaCO_3$ is 1,676 mg l^{-1}, which is classified as very hard. Water alkalinity as calcium carbonate varies widely from a minimum of 120 mg l^{-1} to a maximum of 280 mg l^{-1}, with the average value being 178 mg l^{-1}.

The dissolved solids distribution in the Khobar aquifer covers a quite significant range from slightly less than 2,500 mg l^{-1} to more than 13,000 mg l^{-1}. Maximum and minimum values for EC are 19,840 and 3,600 μS/cm, respectively. As one would expect, dissolved solids concentrations appear to increase with increasing electrical conductivity values. A linear regression performed on the data of these parameters showed a statistically significant positive correlation, with an R^2 value of 0.98. The average ratio of the TDS to the EC values was found to be 0.64. This relationship is shown in Figure 4.3, and provides a good estimate for the TDS from EC field measurements.

All the cations and anions analysed show considerable variations. Calcium averages at 411 mg l^{-1}, but this includes wide ranges from 208 – 882 mg l^{-1}. The magnesium concentration varies from 29 mg l^{-1} to 407 mg l^{-1}. Sodium is the most dominant cation in the Khobar groundwater, and varies from 305 to 3,577 mg l^{-1}. The mean value for potassium is 51 mg l^{-1}, the maximum is 142 mg l^{-1}, the minimum is 15 mg l^{-1}. Chloride is the most predominant anion in the samples analysed, with concentration ranging from 798 to 6,523 mg l^{-1}. Sulphate and bicarbonate analysis indicates concentrations in the range from 405 to 2,100 mg l^{-1}, and from 46 to 342 mg l^{-1}, respectively. Carbonate was not present in all the samples analysed.

Fluoride in the Khobar water reaches a maximum value of 2.1 mg l^{-1}, but its average concentration of 1.36 mg l^{-1} is within the normal limits. Concentrations of boron range from 0.4 to 1.2 mg l^{-1}. Nitrite (as nitrogen) content ranges from 0.0 to 0.11mg l^{-1}. Nitrate-nitrogen presents in the Khobar groundwater in concentrations varying between 1.2 to 11.5 mg l^{-1}. Total iron as Fe varies in concentration from 0.05 to 0.85 mg l^{-1}. All the samples yielded ammonia, phosphorous, aluminum, cobalt, copper, zinc, nickel, and

Figure 4.3 The relation between the dissolved solids concentration and electrical conductivity - Khobar aquifer

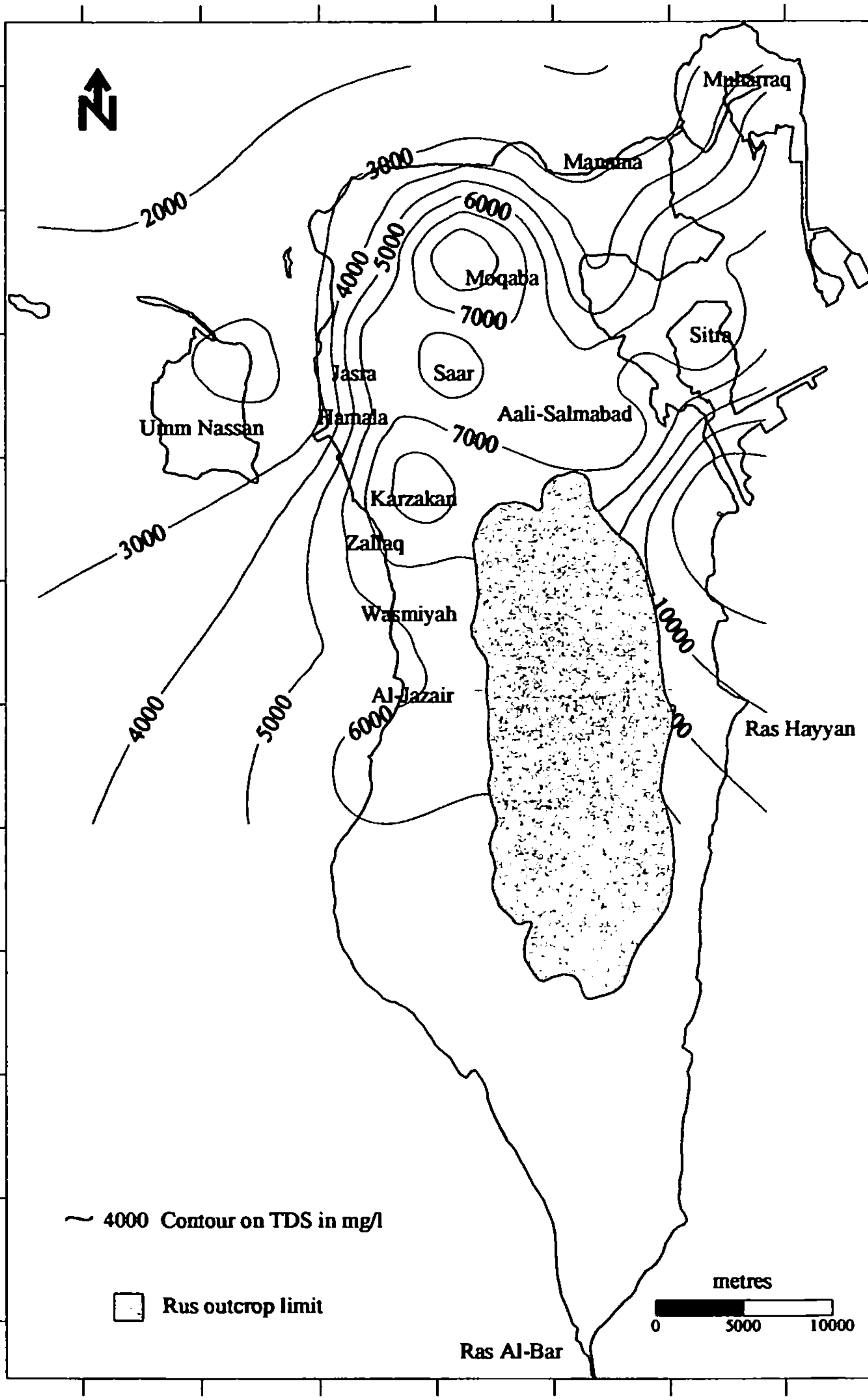


chromium concentrations of lower than 0.01 mg l^{-1}. Lead, cadmium, and manganese are only found in trace amounts of less than 0.001 mg l^{-1}.

The spatial distribution of total dissolved solids concentrations in the Khobar aquifer is illustrated in Figure 4.4. The trend in the figure supports the view that the pattern of TDS distribution generally increases in the direction of decreasing heads. The best quality water occurs in the northwestern region and extends eastwards as far as the Saar scarp. Studies show (Wright, 1967; GDC, 1980b; 1983a) that this water represents the native meteoric water received by throughflow from Saudi Arabia mainland. It has a current (2000) salinity level of between 2,200 – 4,500 mg l^{-1} TDS. Beyond the scarp zone near Aali-Salmabad area, however, salinity markedly increases up to 9,000 mg l^{-1} TDS, consequent upon saline water upflow from the deeper Rus - Umm Er Radhuma aquifer through the non-anhydritic Rus, and lack of efficient aquitard properties. This anomalous trend is evidently related to gradient modification.

Increasing salinity along groundwater flow paths is attributed to modern seawater intrusion. In the southeastern coast, the unconfined Khobar is in direct contact with the sea, and is completely invaded by seawater (TDS values of 44,000 mg l^{-1} and 5,4041 mg l^{-1} are reported in wells 1123 and 1581, respectively, located in Ras Hayyan area). Active flow is also restricted along the southwestern coast near Wasmiyah and Al-Jazair areas, resulting in saline groundwater. Flow restrictions and lack of a flushing process evidently extend further south near Ras Al-Bar and Huwar Islands (Gulmon, 1941), as no Dammam groundwater of good quality has been encountered in these areas since the early developments. Exploratory drilling carried out by BAPCO as part of their structural drilling programme indicated Dammam groundwater having salinities normally

Figure 4.4 Spatial distribution of total dissolved solids in the Khobar aquifer 1999/00



greater than 10,000 mg l^{-1} TDS. The reason for this phenomenon is not well understood, but it could be related to some form of structural control (GDC, 1980b). Recent water quality data (GDC, 1980b; Al-Noaimi, 1993) indicate possible infiltration from sabkha, which may also contribute to restriction of active flow. More recently, between September 2001 and May 2002, drilling investigations carried out in Huwar Island by the WRD indicated highly saline Khobar groundwater of generally more than 30,000 mg l^{-1} TDS.

In localised areas, groundwater salinity in the Khobar aquifer increases to up to 8,000 mg l^{-1} TDS (Figure 4.4). This reflects modifications in the hydraulic gradient caused by upconing of saline water in response to localised heavy pumpage. This can clearly be noticed in Moqabah, Saar, Hamala (Luzi), Karzakkan-Malkiyah, and east of Manama regions. Although at a smaller extent, localised salinity degradation may also be observed around the northeastern tip of Umm Nassan Island probably attributed to the recent increase in groundwater withdrawal.

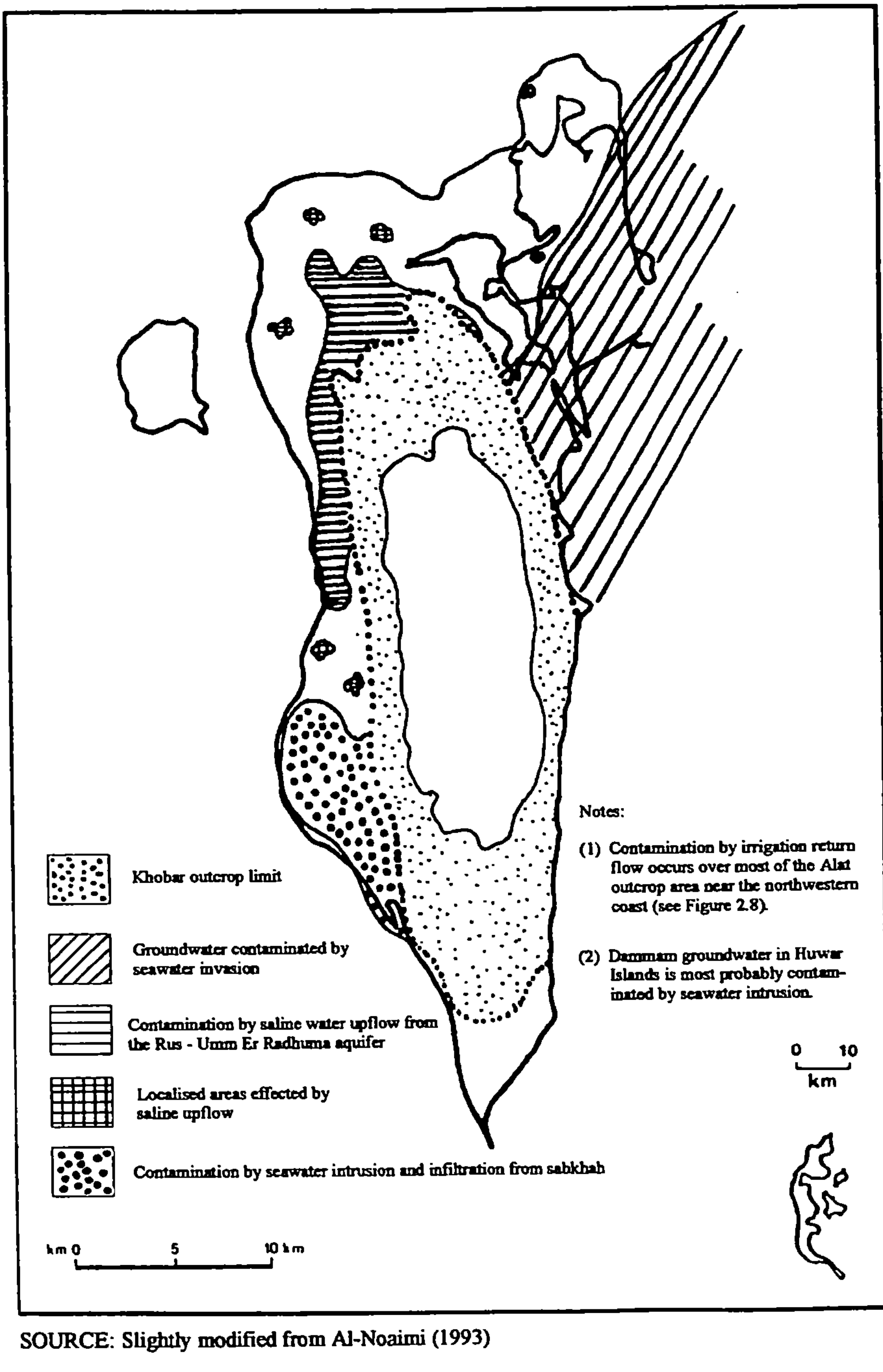
The figure exhibits that the groundwater quality of the Khobar deteriorates rapidly along the highly cultivated lower western areas from Karzakkan down to Zallaq, most probably due to saline water upflow. Within the Hamala-Jasra area, the groundwater tongue of total dissolved solids of between 5,000 – 7,000 mg l^{-1} suggests some sort of salinity adjustment. Several cases of Khobar salinisation by mixing with more saline water have been reported in some isolated wells (TDS of 6,656 mg l^{-1}, and 9,044 mg l^{-1} in wells 1184 and 912, respectively). Because the Rus section in this area is known to contain appreciable amounts of anhydrite and shale, and such salinisation is only observed in isolated wells, it is more likely that saline water moves upward locally through fracture conduits and vertical joints. This may provide another explanation for the anomalous localised drawdown in the Rus - Umm Er Radhuma aquifer referred to in the preceding chapter, since no pumpage has been documented from this aquifer in the western area.

Around Sitra Island, the Khobar salinity ranges from 6,000 mg l^{-1} to 11,000 mg l^{-1}, marking the advance of the saline front along the eastern coast. Water quality data suggest that upward flow is also occurring under this area, as Well 1274, for example, showed water of TDS reaching 64,000 mg l^{-1} that differs in ionic composition from seawater. The figure also shows saline water tongues moving inland towards the south of Manama and east of Muharraq areas.

It follows that the Khobar aquifer is significantly polluted at various localities. The type and extent of pollution to the Khobar groundwater based on the chemical analysis data of 19991/92 (Al-Noaimi, 1993) is illustrated schematically in Figure 4.5. By comparing this figure with the recent TDS trends in Figure 4.4, it could be reasonably said that, apart from minor improvements and degradations in the recent salinity pattern, the magnitude of pollution shown in Figure 4.5 generally reflects the current extent of the aquifer contamination.

Table 4.3 presents descriptive statistics of the TDS and major ions values of groundwater analyses from the Khobar aquifer for1991/92 and 1999/2000. Paired sample t-statistics for the mean values of these parameters are presented in Table 4.4. The results showed significant differences at 95% level of confidence ($p < 0.05$) with respect to the TDS, chloride, sulphate, sodium, calcium, and magnesium, whereas no significant difference was found in the case of bicarbonate, and potassium mean concentrations. The mean TDS

Figure 4.5 Map showing the extent of groundwater contamination to the Dammam aquifers



SOURCE: Slightly modified from Al-Noaimi (1993)

Table 4.3 Statistical summary of total dissolved solids and major ions concentrations of groundwater from the Khobar aquifer 1991/92 and 1999/00

	Al-Noaimi (1993)							Present investigation (2004)						
Parameter	n	mean	Standv.	mode	median	min.	max.	n	mean	standv.	mode	median	min.	max.
TDS	237	4542	2919	2240	3290	2200	29800	263	5186	2264	2295	4821	2210	13494
Chloride	94	1794	1880	990	1274	788	16383	263	2259	1187	1347	1990	798	6523
Sulphate	94	733	440	441	554	225	2722	263	917	385	600	775	405	2100
Bicarbonate	90	219	36	212	214	98	349	263	220	28	220	214	46	342
Sodium	94	918	974	505	669	421	9000	263	1174	598	636	1053	305	3577
Calcium	94	326	151	220	254	177	836	263	411	163	240	377	208	882
Magnesium	94	130	116	74	99	57	1101	263	158	70	83	146	29	407
Potassium	90	50	43	28	39	24	372	260	50	25	29	45	15	142

Notes: [1] Mean, maximum and minimum parameters values are expressed in milligram per litre (mg l^{-1}).
[2] Some values are rounded to the nearest decimal.

Table 4.4 Paired sample *t*-statistics for groundwater samples from the Khobar aquifer 1991/92 – 1999/00

Parameter	Std. error of mean	*t*-statistics	95% confidence interval of the difference		*p* - value
			lower	upper	(two-tailed)
TDS	239.89	-3.034	-1200.50	-255.31	0.003
Chloride	223.70	-2.504	-1004.27	-115.85	0.014
Sulphate	65.69	-3.985	-392.25	-131.34	0.000
Bicarbonate	4.67	0.307	-7.85	10.72	0.760
Sodium	115.68	-2.768	-549.90	-90.45	0.007
Calcium	23.63	-4.190	-145.95	-52.09	0.000
Magnesium	14.06	-2.206	-58.91	-3.09	0.030
Potassium	48.79	-0.510	-12.84	7.60	0.611

value has increased from 4,542 mg l^{-1} to 5,186 mg l^{-1}, an increase of 14 %. Chloride has increased by about 26 % from an average of 1,794 mg l^{-1} to 2,259 mg l^{-1}. The average level of sodium increased significantly from 918 to 1,174 mg l^{-1}, representing about 28 % increase. Sulphate and calcium concentrations have risen by about 25 % and 26%, respectively, during the comparison period. Magnesium content has showed an average increase of 21% from 130 mg l^{-1} to 158 mg l^{-1} over the two sampling periods.

Eighty seven of the wells sampled as part of the 1991/92 countrywide water quality survey (Al-Noaimi, 1993) were also available for sampling during the second sampling period of this investigation (1999/00). Table C-3 of Appendix C gives the total dissolved solids data of these wells. Descriptive statistics for analyses of wells sampled over the two sampling periods is given in Table 4.5. With regard to the TDS, the result is significant at the 5% level, and shows an increase of 18% over the interval years from a mean value of 4,187 mg l^{-1} to 4,962 mg l^{-1}.

Table C-3 indicates that about 75 % of the wells sampled in the two surveys have shown increases in the TDS values, ranging between 2 % to greater than 200 %. The maximum increases were noted in Moqabah and Shakhoora areas, with well 10/44 in Moqabah showing nearly 207 % increase, whilst the minimum increases were reported from wells in the western and north-central parts. Twenty-two wells (25 %) have shown a decreasing pattern in salinity, ranging from 2 to 35 %. However, considering possible analytical errors and seasonal variations, the salinities in some of the wells appear to have remained constant.

These TDS values have been presented in the form of contour difference map over the two

Table 4.5 Descriptive statistics of the groundwater chemistry of the Khobar aquifer 1991/92 and 1999/00

Parameter	Al-Noaimi (1993)							Present investigation (2004)						
	n	mean	standv	mode	median	min.	max.	n	mean	standv.	mode	median	min.	max.
TDS	87	4187	1815	2600	3665	2200	10100	87	2046	1897	2295	4730	2295	11629
Chloride	35	1603	706	1055	1283	822	3834	85	2046	829	1241	2021	851	3999
Sulphate	35	771	482	441	600	225	2722	85	918	389	700	760	422	2000
Bicarbonate	35	225	33	213	218	121	312	85	224	25	207	220	188	319
Sodium	35	863	448	675	690	455	2783	85	1073	428	680	1094	438	2085
Calcium	35	338	146	220	283	199	736	85	399	154	257	356	208	842
Magnesium	35	129	59	90	113	57	292	85	152	60	102	151	29	267
Potassium	35	47	21	30	40	24	122	85	47	19	30	47	18	100

Notes: [1] Mean, maximum and minimum values are expressed in milligram per litre (mg l^{-1}).
[2] Some values are rounded to the nearest decimal.

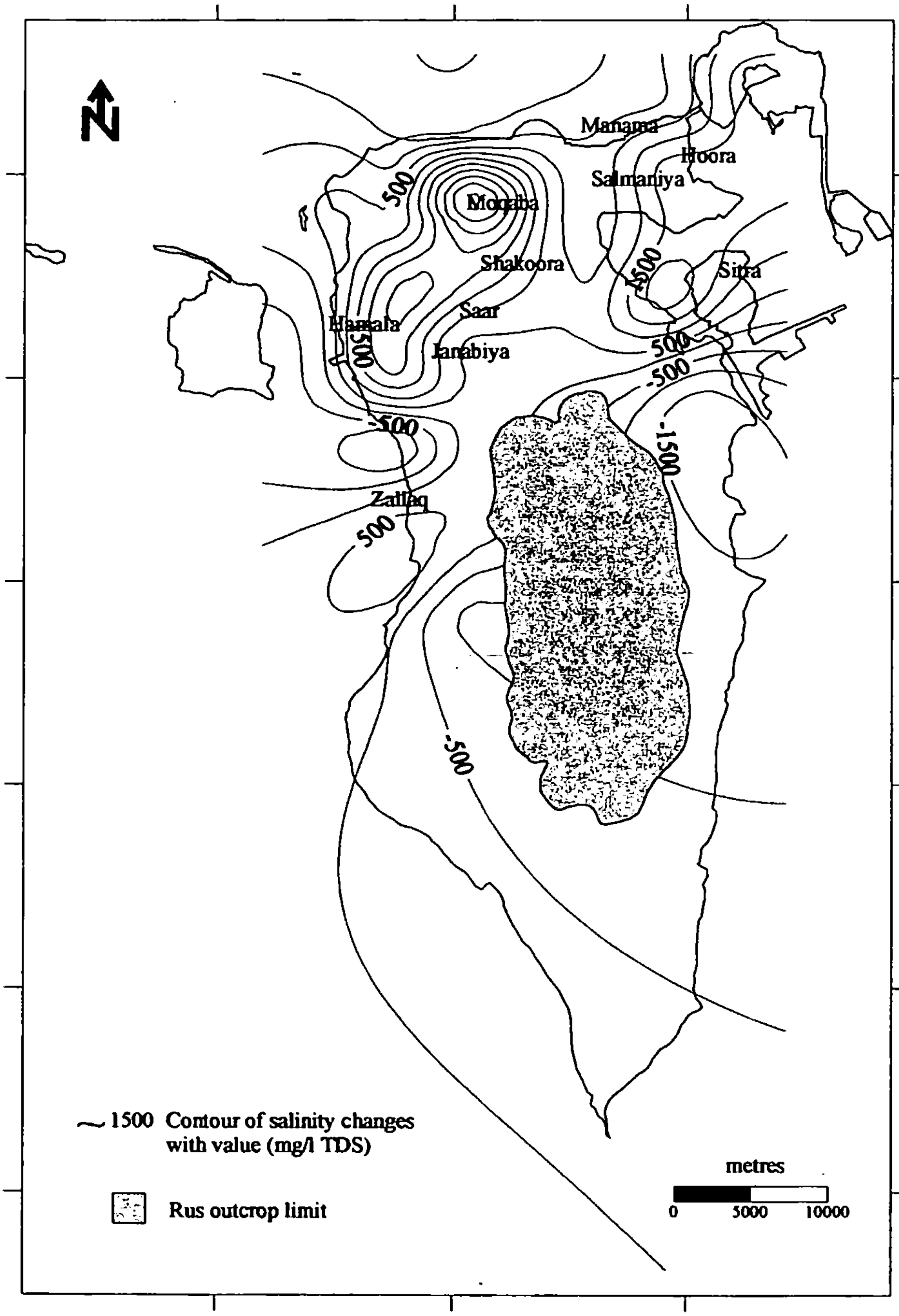
sampling periods as shown in Figure 4.6. A general view of this figure indicates a decreasing TDS pattern (negative values) in the southeastern coast in 1999/2000 from that observed in 1991/92. A slight improvement in salinity is shown by the -500 mg l^{-1} salinity contour in parts of the lower western coast, probably in conformity with the water levels behaviour discussed earlier. Most of the wells in the upper western coast have recorded salinity increase from about 500 to 1,500 mgl^{-1}. A maximum increase to up to a 2,500 mg l^{-1} can be seen near the Saar scarp line, intimately in association with the cone of depression noticed in Janabiyah and Hamala areas (refer to the discussion in Chapter Three, page 253).

The TDS distribution in the northern coast is nearly unchanged, but further inland from this coast towards Moqabah and Shakhoora, the Khobar salinity has deteriorated significantly, with some wells showing up to a 3,000 mg l^{-1} increase. It is interesting to note that the improvement gained near the major pumping centres in Great Manama area, including Hoora, Mahooz and Sulmania areas in particular during the 1991/92 survey (Al-Noaimi, 1993) has been reversed. A salinity increase of between 1,000 to 2,500 mg l^{-1} is recorded in these areas. Notably, this pattern of salinity degradation is also observed in the northern parts of Sitra, compared with the improvement trend recorded in this area during the Al-Noaimi (1993) survey. Salinity in the northeastern coast has also shown an increasing trend. No significant salinity changes have occurred in the north-central area, which is consistent with the piezometric heads evidence.

Sodium Adsorption Ratio and Boron

Because groundwater from the Khobar aquifer is extensively used for agriculture, its suitability for irrigation has been assessed. For this, the major cations, excluding the

Figure 4.6 Contour map of total dissolved solids changes in the Khobar aquifer 1991/92 - 1999/2000



potassium, were used to determine the sodium (sodicity) hazard of the irrigation water by calculating the SAR value. The equation used to determine this ratio (Richards, 1969) is:

$$SAR = \frac{Na}{\sqrt{\frac{(Ca + Mg)}{2}}}$$

Where: Na, Ca, and Mg are given in milliequivalents per litre (meq/l)

For the purpose of calculating the SAR values for the Khobar groundwater, the agricultural areas in Bahrain were divided into five agricultural regions. The range and average SAR values for selected ten water samples from each region are presented in Table 4.6. The average SAR value indicates an S2 water (medium sodium hazard), according to Richards (1969), who proposed the diagram that classifies the irrigation waters in terms of SAR as an index for sodium hazard and the EC as an index for salinity hazard. The calculated SAR values are plotted on this diagram as illustrated in Figure 4.7. It can be seen that the majority of the irrigation water in the study area is grouped in the C4-S2 class (very high salinity with medium sodium hazard), but may be confidently classified between C4-S1 and C4-S2 (very high salinity, low - medium sodium hazard).

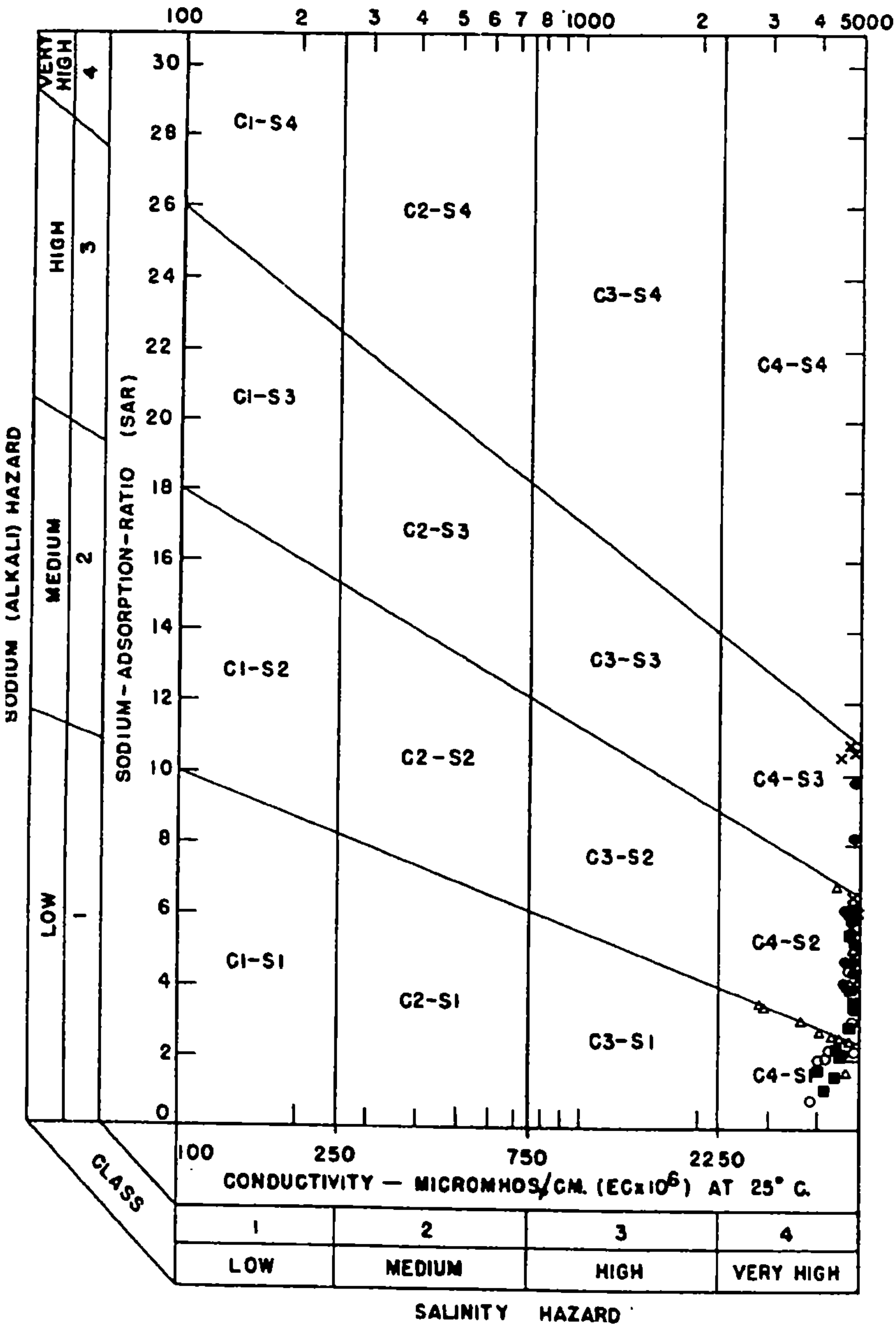
Most of the northern and upper western coasts groundwaters are of low sodium hazard, whilst groundwaters from the other regions are characterised to have a quality water class of C4-S2, which indicates medium sodium hazard. This suggests that, even though the irrigation waters in the study area are very saline, sodicity problems are relatively low to moderate owing to the enhanced calcium contents. Such water may be used for irrigation under special circumstances: fine-textured, highly permeable, and gypsum-rich soils, as

Table 4.6 Sodium Adsorption Ratio (SAR) and boron content in groundwater from the Khobar aquifer

Agricultural region	Sodium Adsorption Ratio (SAR)		Boron content (mg l^{-1})	
	Range	Average	Range	Average
Northern coast	6 - 14	9.4	0.5 – 0.8	0.6
Northeastern coast	7 – 16	10.3	0.4 – 0.7	0.53
Upper western coast	7 – 13	9.9	0.5 – 0.6	0.56
Lower western coast	12 – 22	14.7	0.6 – 1.0	0.72
Eastern coast	12 – 24	15.8	0.6 – 0.7	0.63
Average Value		12.0		0.61

Note: The upper western coast designates the area from Budaiya to Hamala, while the lower western coast are those areas from Dumistan in the north down up to Al-Jazair.

Figure 4.7 Classification of the irrigation water in the study area on the basis of sodium and salinity hazards



EXPLANATION

△ Northern coast × Eastern coast ○ Upper western coast

● Lower western coast ■ Northeastern coast well as presence of drainage and leaching practices (Richards, 1969); such conditions and farming practices are exist and being followed in Bahrain.

Boron concentration in groundwater plays an important role in determining its suitability for irrigation. Its concentration in irrigation water is, however, sensitive because it is essential for plant growth up to a certain very small concentration, and if this is exceeded, it becomes toxic and may cause injury to some plants (Richards, 1969). Table 4.6 also provides ranges and averages of boron contents in groundwater from the Khobar aquifer for the same agricultural regions. The permissible limits of boron for several classes of irrigation waters as proposed by Wilcox (1955) are given in Table 4.7.

Table 4.7 Permissible limits of boron concentration for various classes of irrigation waters and crop tolerance levels

Classes of water		Sensitive crops	Semi-tolerant	Tolerant crops
Rating	Grade	(mg l^{-1})	crops (mg l^{-1})	(mg l^{-1})
1	Excellent	<0.33	<0.67	<1.00
2	Good	0.33 – 0.67	0.67 – 1.33	1.00 – 2.00
3	Permissible	0.67 – 1.00	1.33 – 2.00	2.00 – 3.00
4	Doubtful	1.00 – 1.25	2.00 – 2.50	3.00 – 3.75
5	Unsuitable	>1.25	>2.50	>3.75

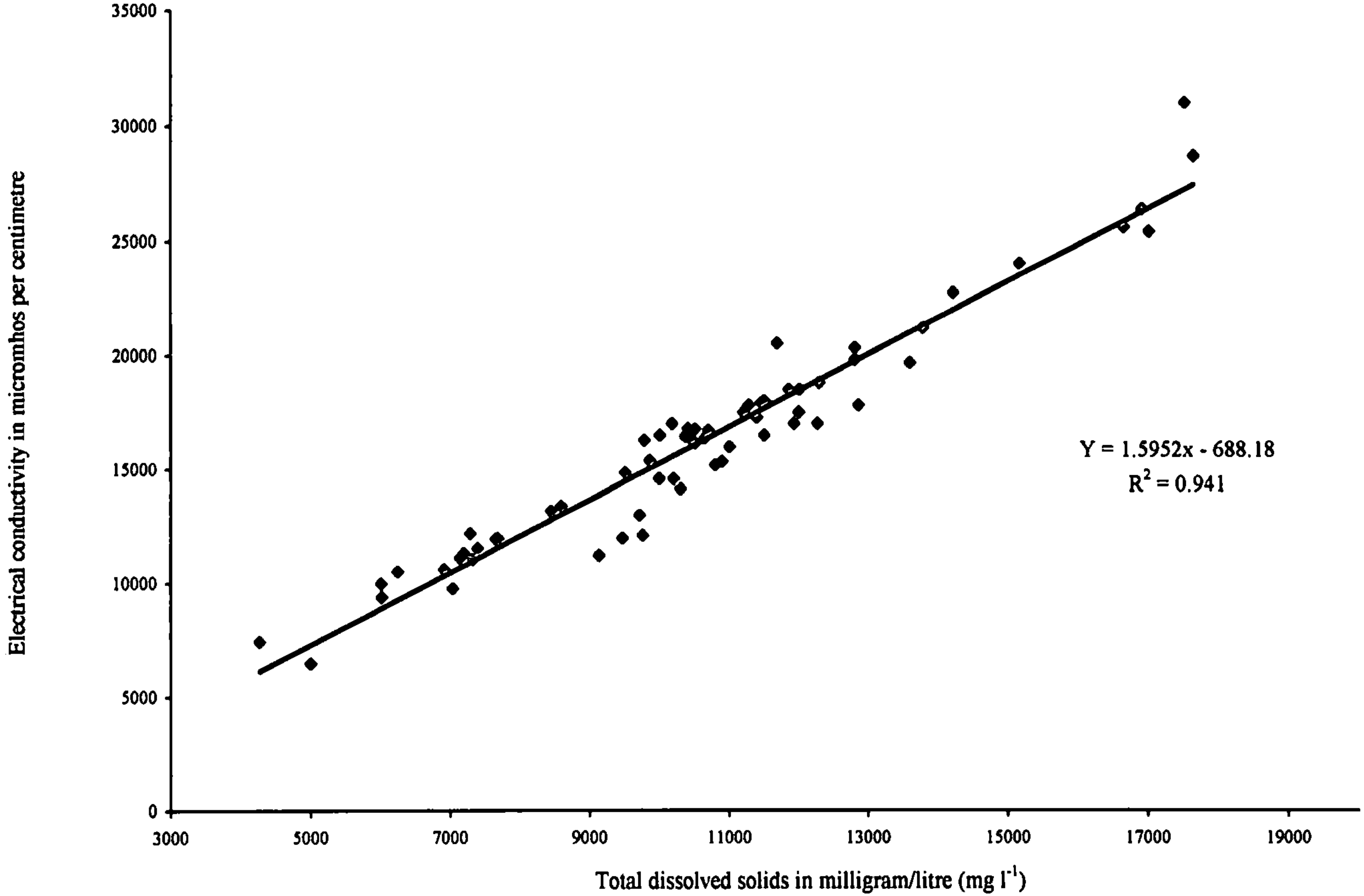
Comparison of these values with those presented in Table 4.6 indicates that the irrigation water in the study area is graded as excellent for the boron-tolerant crops in all the agricultural regions considered. This is also the case with the boron semi-tolerant crops, with the exception of the lower western coast region, which shows boron average concentration of slightly higher than the permissible limit. The irrigation waters can also be classified as good for the sensitive and semi-tolerant crops. The Khobar water of concentration ranges from 0.4 – 1.2 mg l^{-1} with respect to boron (see Table C-2) is suitable for irrigation purposes, especially that most of the crops cultivated in Bahrain are confined to the boron-tolerant group. The international guidelines for interpretation of water quality for irrigation (FAO, 1985) suggest a guideline level of less than 0.7 for boron-sensitive crops, and between 0.7 – 3.0 for the semi-tolerant and some of the tolerant crops, which are similar to the limits suggested by Wilcox (1955).

4.3 The Rus - Umm Er Radhuma Aquifer

The chemical analysis of water samples from the Rus - Umm Er Radhuma are appended in Table C-4 of Appendix C. The table shows that the pH values of the samples ranged from 6.2 – 11.1. A few measurements (not included in the table) reported by GDC during the 1980 and 1983 investigations show Eh values for this aquifer ranging from –18 to –245 mV, indicating a slightly reducing character. Previous analysis (GDC, 1980b) also suggests that the normal Rus - Umm Er Radhuma water contains hydrogen sulphide (H_2S) in the range of 0.5 – 8.0 mg l^{-1}. The values of EC varied significantly, ranging from 6,500 – 31,000 μS/cm. All the Rus - Umm Er Radhuma wells yield water with TDS content in excess of 4,000 mg l^{-1}, ranging from 4,269 mg l^{-1} to 17,630 mg l^{-1}. The relationship relating the EC and TDS values for this aquifer produces a strong linear correlation with R^2 value of 0.94, and a constant value equal to 0.65. This relation is shown in Figure 4.8.

The Rus - Umm Er Radhuma water is very hard. Total hardness as $CaCO_3$ ranges between 1,100 – 3,950 mg l^{-1}. Total alkalinity as $CaCO_3$ is between 30 to 1,790 mg l^{-1}. Concentrations of major ions show average values of calcium and magnesium of 599 and

Figure 4.8 The relation between the total dissloved solids and electrical conductivity - Rus - Umm Er Radhuma aquifer

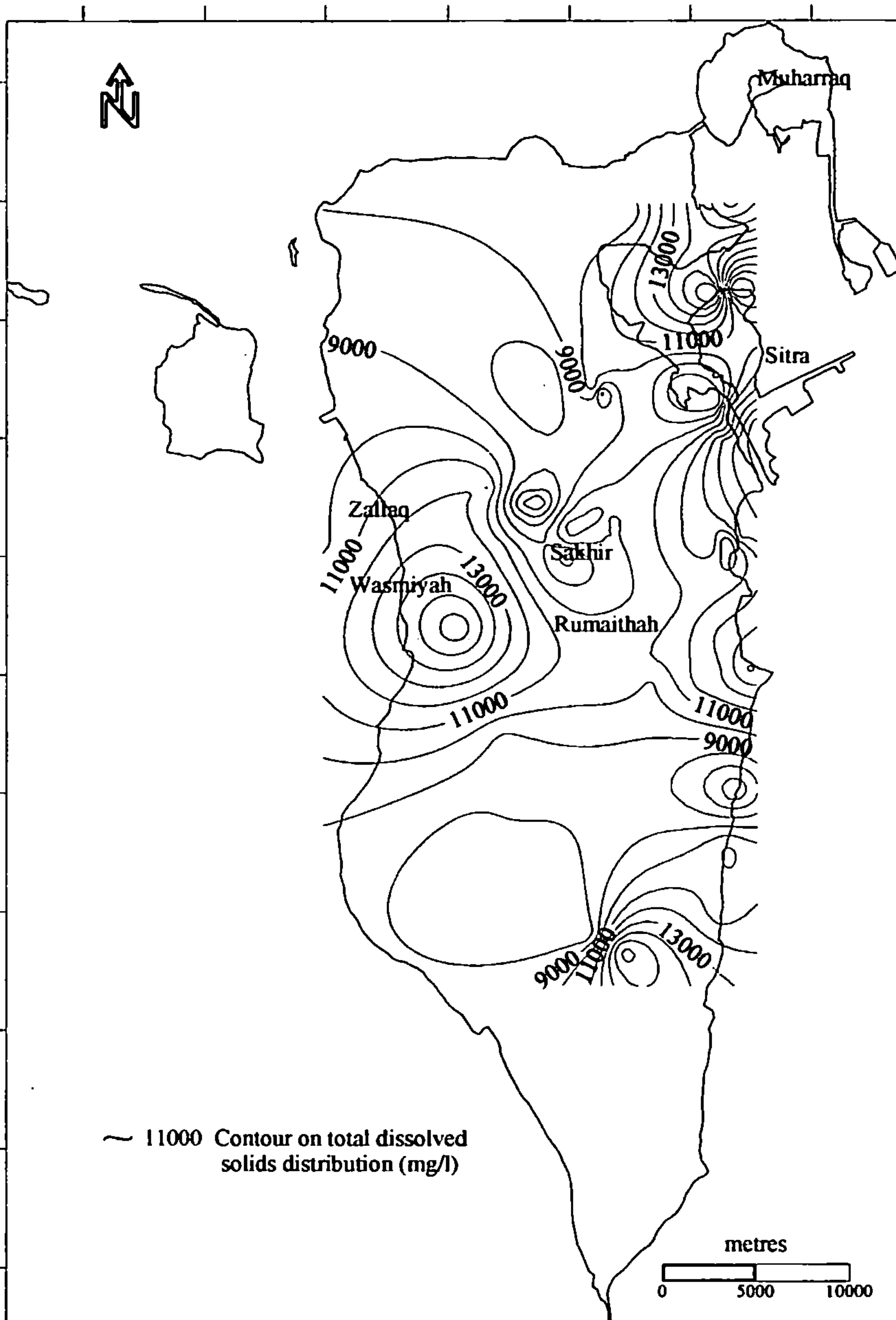


266 mg l^{-1}, respectively. Maximum and minimum values for sodium are 6,440 mg l^{-1} and 1,113 mg l^{-1}, respectively; the average is 2,890 mg l^{-1}. Potassium contents ranged from 7.8 to 274 mg l^{-1}, and averaged at 146 mg l^{-1}. Chloride concentrations range from 2,148 to 10,650 mg l^{-1}, while those of sulphate range between 96 and 3,312 mg l^{-1}. Carbonate was only found in four samples, with concentrations ranging from 1.5 to 123 mg l^{-1}. The bicarbonate is found to vary widely from 24 to 427 mg l^{-1}, with two samples having nil mg l^{-1} of bicarbonate.

The TDS contour map of the Rus - Umm Er Radhuma aquifer is shown in Figure 4.9. It is evident that no salinity trend is readily apparent in this map; however, TDS concentrations of normally less than 9,000 mg l^{-1} are generally restricted to the core region where the Rus Formation crops out, particularly near Sakhir and Rumaithah. This water probably represents a mixture between the native Rus - Umm Er Radhuma groundwater and water of recent meteoric recharge, which has apparently reduced the TDS concentrations. The shallow depths of the wells sampled in this area could also be a possible explanation. Groundwater of relatively lower TDS values in the north-central areas may reflect a contribution from Khobar water. To the west of Sitra Island, a pocket of lower salinity waters is also discernible.

The normal Rus - Umm Er Radhuma brackish groundwaters with salinity between 11,000 – 15,000 mg l^{-1} as total dissolved solids occurs along the eastern and southeastern coasts, and appears to exist around Wasmiyah and Zallaq areas as well. The map also suggests that the normal brackish water salinity probably extends northeastwards as far as Muharraq Island, although recent chemical analysis from this area (well WRD 1663 - not included in this survey) show salinity as high as 32,362 mg l^{-1}. This possibly indicates

Figure 4.9 Total dissolved solids distribution in the Rus - Umm Er Radhuma Aquifer 1983 - 2000



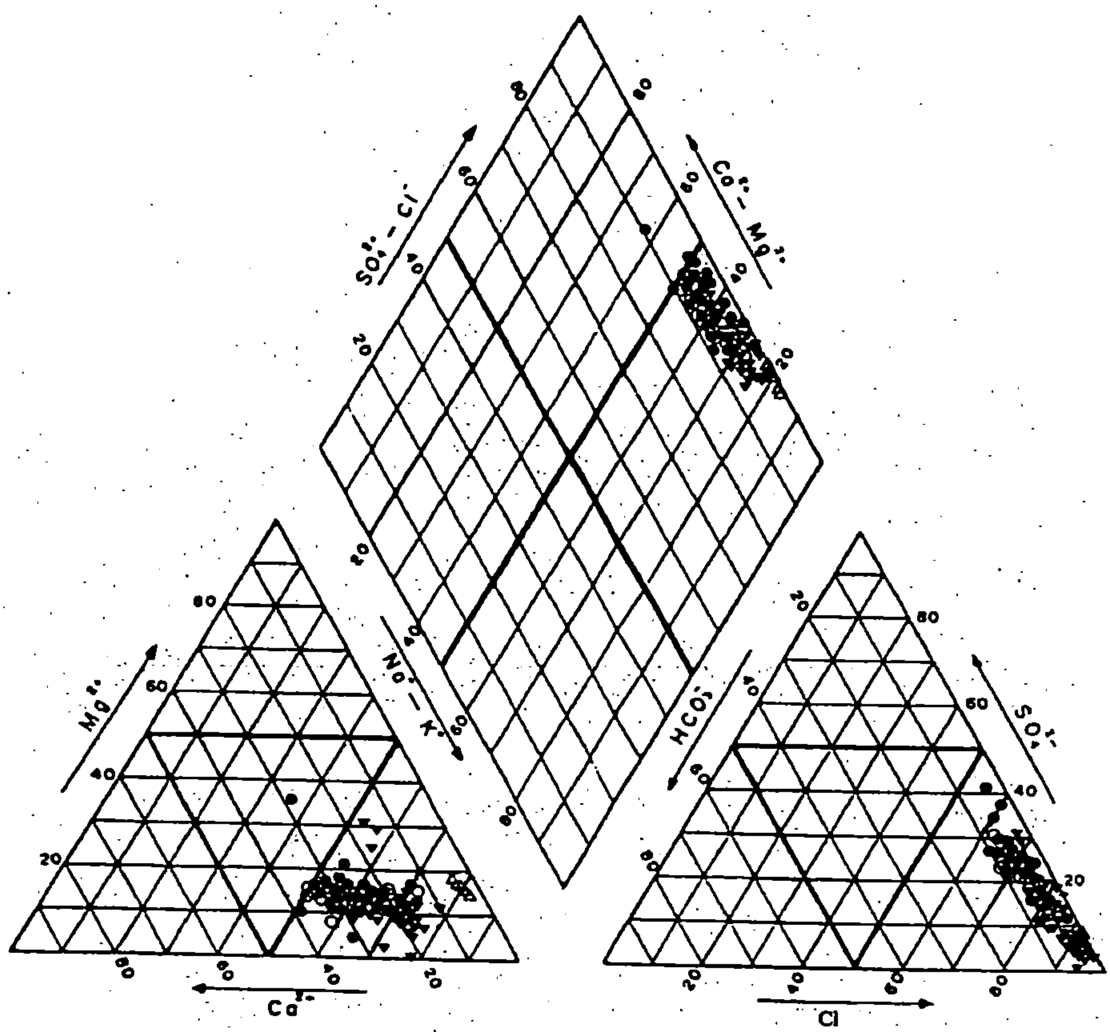
that the brackish water lens does not exist beyond the Manama area; a speculation closely consistent with the GDC assumption regarding the occurrence and extent of the brackish water lens.

The data in Table C-4 primarily represent the salinity pattern in the Rus - uppermost Umm Er Radhuma. Studies (GDC, 1980b; 1983a; Zubari, 1994) have demonstrated that groundwater salinity in this aquifer varies considerably with depth. Depth sampling in the Rus - Umm Er Radhuma aquifer has shown a linear TDS gradient of about 180 mg l^{-1} per metre below a depth of about 120 m (GDC, 1980b). Salinity profile tests performed by GDC (1980b) indicated three depth zones with a marked salinity stratification. These are the upper zone with TDS of between 7,000 – 15,000 mg l^{-1}, intermediate or transitional zone of TDS between 15,000 – 45,000 mg l^{-1}, and a lower zone that contains highly saline or brine water of up to 100,000 mg l^{-1}. The brine exists in rocks stratigraphically of the lowermost Umm Er Radhuma and upper Aruma Formations with strongly reducing behaviour, and a very high H_2S concentration of up to 125 mg l^{-1}, indicating old connate water residence in stagnant conditions (GDC, 1980b).

4.4 Hydrochemical Facies

This section examines the groundwater chemical characters, genetic types, evolutionary patterns, and mixing trends in the area of study. The Piper trilinear diagram (Piper, 1944), and the Durov diagram (Durov, 1948) are widely used to represent the hydrochemical facies and water chemical types of natural waters. Trilinear and Durov plots of major chemical constituents of groundwaters and seawater in the study area are shown in Figures 4.10 and 4.11, respectively. These plots represent all the chemical data from the Alat Limestone and Rus - Umm Er Radhuma aquifers, whilst, for convenience, only 75

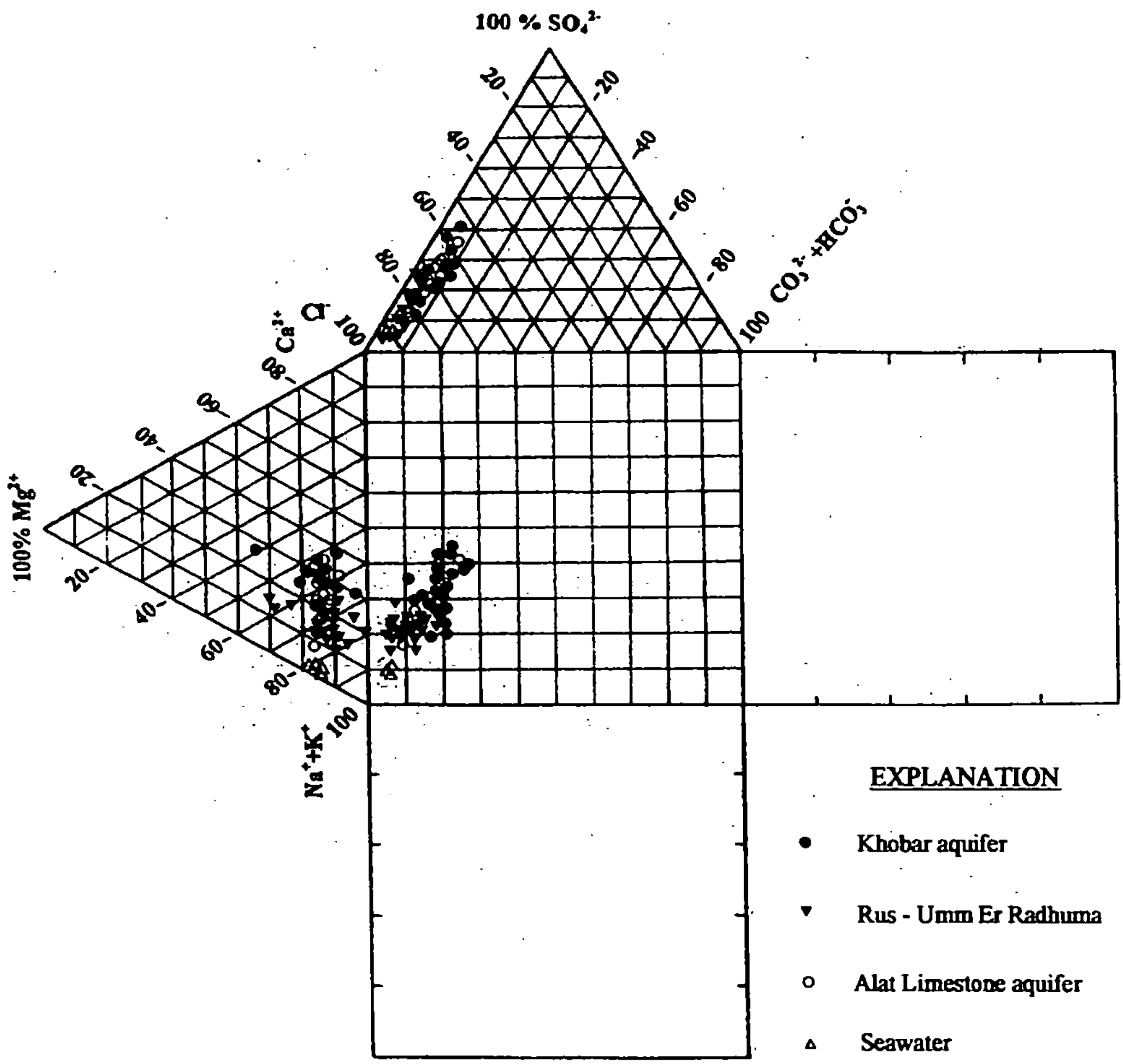
Figure 4.10 Trilinear diagram showing the relationship between water chemistry of groundwater and water chemistry of seawater



EXPLANATION

- ● Khobar aquifer
- ○ Alat Limestone aquifer
- ▼ Rus - Umm Er Radhuma
- △ Seawater

Figure 4.11 Durov diagram representing groundwaters from the Alat Limestone, Khobar, and Rus - Umm Er Radhuma aquifers and seawater



samples were randomly selected to characterise the Khobar aquifer, on the basis of salinity ranges within the aquifer with due consideration for the samples' areal distribution. A total of 10 seawater samples from different locations were used in these plots.

The plots clearly show that groundwaters in the study area are dominated by alkalis (Na^+, K^+) and strong acids (Cl^-, SO_4^{2-}), and are of sodium-chloride type, characterised by primary salinity. Although they differ greatly in total concentration, the chemical character and predominant cation and anion sequences are similar in both the Dammam and Rus - Umm Er Radhuma aquifers. The predominant cation sequence is $Na^+ > Ca^{2+} > Mg^{2+}$, whereas the predominant anion sequence is $Cl^- > SO_4^{2-} > HCO_3^-$. These water types indicate old brackish groundwater, typical of a discharge area. Only one sample from the Khobar aquifer shows increases on the Ca^{2+} and Mg^{2+} values on the expense of Na^+, possibly due to calcite and/or gypsum precipitation or solution. This sample plots on the field of permanent hardness at the upper part of the diamond of the Piper diagram (Figure 4.10). The water of this sample is extremely hard compared to its salinity. Irrespective of variation in the TDS contents, water from the Dammam and Rus - Umm Er Radhuma aquifers plot in approximately the same field. As can be seen from the figures, seawater has a different composition from the groundwaters in the study area and plots slightly away from them. The uniformity in chemical water type and absence of pattern variations throughout the study area do not allow a system of hydrochemical facies zonation.

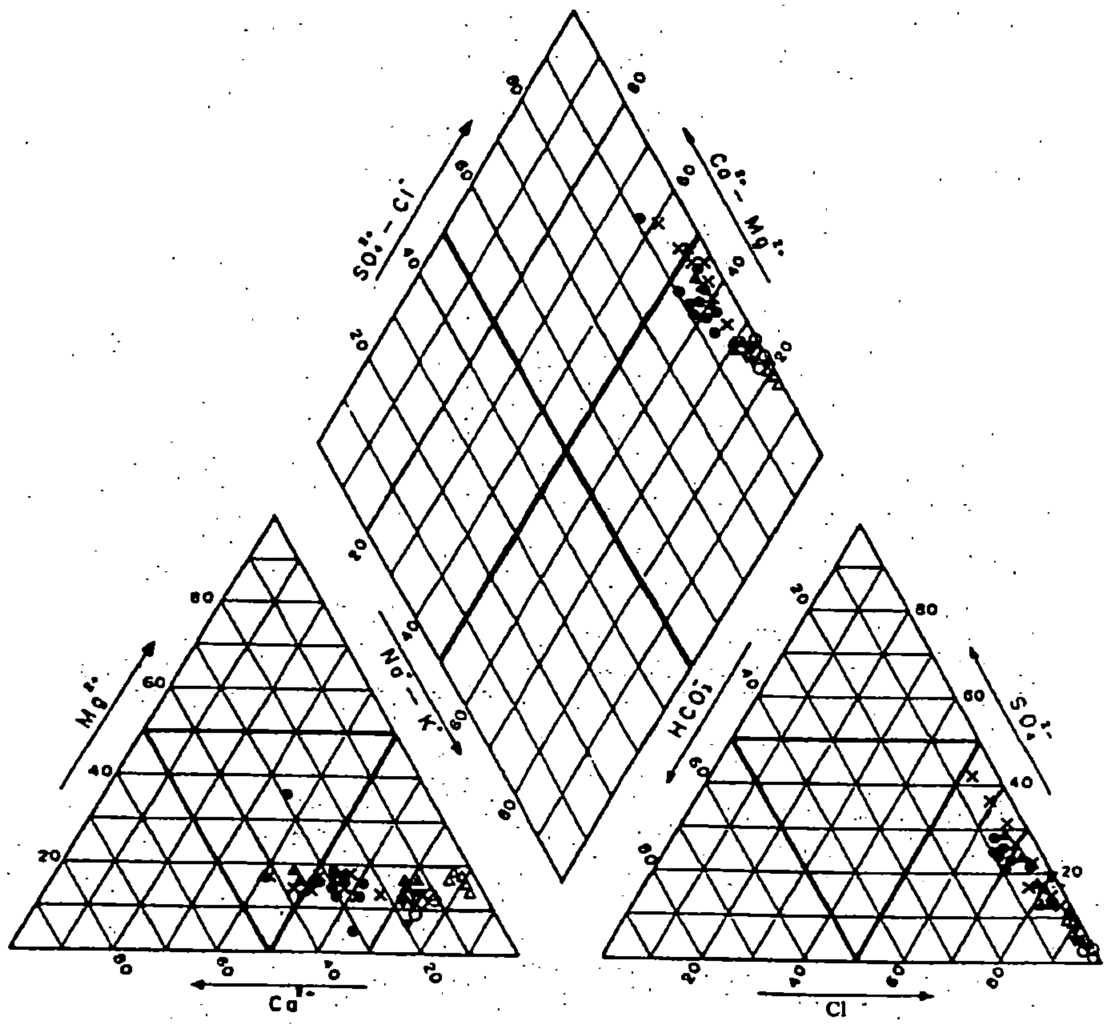
Mixing between groundwaters from the Dammam and Rus - Umm Er Radhuma aquifers, and Dammam and seawater has already been demonstrated from the areal trends. However, a random selection of ten samples of groundwater from the native Dammam and Rus - Umm Er Radhuma are plotted on the Piper and Durov diagrams (Figures 4.12 and 4.13) against ten analysis from each of seawater, Dammam groundwater contaminated by seawater, Dammam groundwater contaminated by upconing of saltwater from the Rus - Umm Er Radhuma, and brine water of the lower Umm Er Radhuma (only six samples were made available from this source). It can be clearly seen that the native Dammam groundwater plots in a straight line between seawater and Dammam groundwater invaded by seawater, indicating a simple mixing relationship between these two end members.

In contrast, the presumed mixing between native Dammam (Khobar) and Rus - Umm Er Radhuma groundwaters shows a rather complex relationship. Here, the plot of the resultant contaminated water slightly deviates from the ideal mixing line, probably due to the relative increase in Ca^{2+} on the expense of Na^{+}, and release of SO_4^{2-} due to dissolution of gypsum. Such a complex mixing can be attributed to the reverse cation exchange process (see Appelo and Postma, 1999; Hounslow, 1995). This mixing relationship is more discernible in the case of Durov plot. The brine from the Rus - Umm Er Radhuma aquifer shows relative increase in Na^{+} possibly owing to the cation exchange process.

4.5 Ionic Ratios

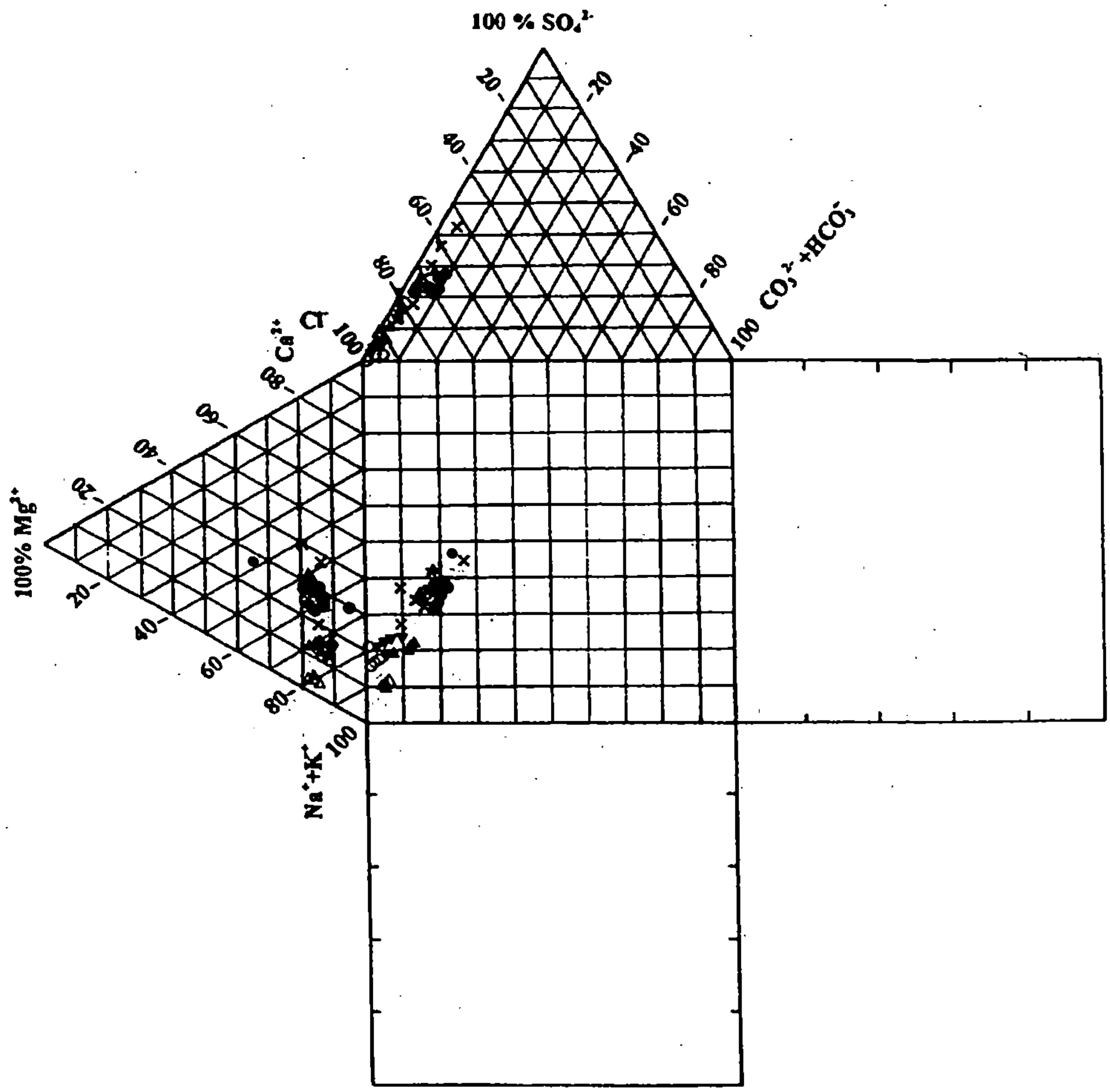
Expression of the relationship among ions in terms of mathematical ratios is often useful in establishing resemblances and differences among different types of natural waters (Hem, 1985). They are also important to identify sources of pollution, movement of groundwater, and to investigate the influence and degree of mixing between different water types. The average values of the major ionic ratios (Na^{+}/Cl^{-}, SO_4^{2-}/Cl^{-}, Ca^{2+}/Mg^{2+}, and Ca^{2+}/Na^{+}) of the native and contaminated groundwaters, and seawater in the study area were calculated as shown in Table 4.8.

Figure 4.12 Trilinear plots showing the water chemistry of native groundwaters, groundwater of mixed origins and seawater



EXPLANATION

Figure 4.13 Durov diagram showing the chemical characters of native groundwaters, groundwater from mixed origins, and seawater



EXPLANATION

- ● Native Dammam (Khobar)
- ▲ Khobar invaded by seawater
- ○ Brine water of lower Umm Er Radhuma
- × Khobar contaminated by upflow from Rus - Umm Er Radhuma
- ▼ Rus - Umm Er Radhuma
- △ Seawater

Table 4.8 Average major ionic ratios of native groundwater, brine, contaminated groundwater, and seawater in the study area

Source	Average of major ionic ratios			
	Na^+/Cl^-	SO_4^{2-}/Cl^-	Ca^{2+}/Mg^{2+}	Ca^{2+}/Na^+
Alat Limestone aquifer	0.81	0.34	1.76	0.46
Khobar aquifer	0.81	0.34	1.70	0.44
Rus - Umm Er Radhuma aquifer	0.80	0.14	1.72	0.25
Dammam invaded by seawater	0.85	0.22	0.90	0.21
Brine water from lower Umm Er Radhuma	1.30	0.02	0.98	0.16
Seawater	0.84	0.11	0.19	0.045

The table reveals close similarity in all sources, including seawater, with respect to the Na^+/Cl^- ratio. It ranges from 0.80 to 0.85; the only exception is the brine water of deep Umm Er Raduma, which exhibits a greater average ratio of 1.30. This similarity reflects the dominance of NaCl cation-anion pair in groundwaters of the study area. The high average ratio in the deep brine indicates distinction in ionic composition of this water that can be explained by the release of Na^+ and relative decrease in Cl^- concentration. This ratio is, therefore, useful in identifying groundwater of brine origin.

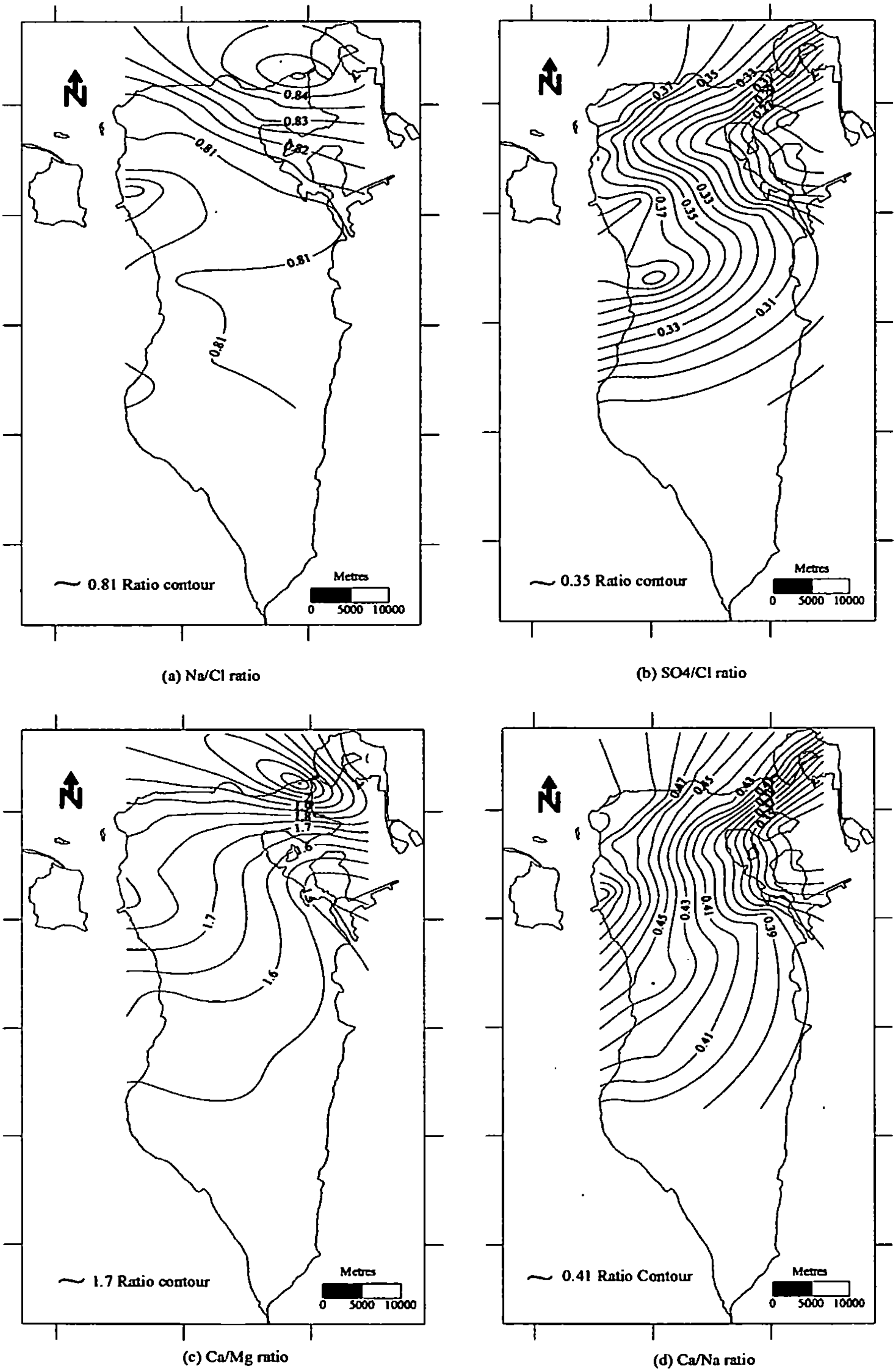
Sulphate concentration is generally low in seawater and brines compared to the chloride (Back, 1960; Hem, 1985), resulting in lower SO_4^{2-}/Cl^- ratio. This is because of possible cation exchange and sulphate reduction that can be expected to occur when seawater is introduced to the system (Hem, 1985). In the native Dammam groundwaters, this ratio reaches 0.34, while it has an average value of 0.11 in seawater. The average SO_4^{2-}/Cl^- ratio of 0.22 in the Dammam groundwater along the eastern coast clearly reflects seawater intrusion. The very low SO_4^{2-}/Cl^- ratio in the brine water indicates increase in Cl^- concentration compared with SO_4^{2-} concentration.

The ratio of calcium to magnesium is useful in studying groundwater from limestone and dolomite, and may also be of help in tracing seawater contamination, as magnesium is present in seawater in much greater concentration than is calcium (Hem, 1985). A low Ca^{2+}/Mg^{2+} ratio may, therefore, be indicative of seawater intrusion. The average value of 0.19 in the Gulf seawater is closely in accord with the average Ca^{2+}/Mg^{2+} in normal seawater (0.20) according to Hem (1985). Analysis of the native Dammam (Khobar) groundwater indicates an average value of 1.73. The mean value of 0.90 observed in the Dammam groundwater invaded by seawater strongly substantiates the simple admixture process already demonstrated by the trilinear plots.

The table shows an average Ca^{2+}/Na^{+} ratio in seawater of 0.045 against a mean value of 0.45 in the native Dammam groundwaters. The brackish Dammam groundwater has an average Ca^{2+}/Na^{+} ratio of 0.21, which falls almost on the midpoint between seawater and fresh groundwater ratios, again suggesting a simple admixture. An increase in concentration of Na^{+} in the brine groundwater of deep Umm Er Radhuma penetration causes low Ca^{2+}/Na^{+} ratio (0.16) compared with those of the native Dammam (Alat and Khobar) and Rus - Umm Er Radhuma groundwaters.

The distribution of the major ionic ratios in the Khobar aquifer is shown in Figures 4.14a to 4.14d. In general, the observed distribution of these ratios seems to be largely controlled by the seawater intrusion process. The distribution of the Na^{+}/Cl^{-} ratio (Figure 4.14a) suggests slightly decreasing trend in the direction of groundwater flow (NW-SE) probably reflecting increase in the chloride concentration associated with the seawater intrusion along the eastern coast. The same interpretation could also be suggested for the trend in the SO_4^{2-}/Cl^{-} ratio (Figure 4.14b), which decreased toward the flow direction. As depicted by Figure 4.14c, the lower Ca^{2+}/Mg^{2+} ratio indicates greater concentration of magnesium along the flow path, which is again indicative of seawater intrusion or dolomitisation process. The distribution pattern of the Ca^{2+}/Na^{+} ratio in Figure 4.14d also indicates decreasing trend in the direction of groundwater movement towards the southeast direction; this is more likely to be attributable to the cation exchange process and/or release of sodium, but seems surprising since it suggests refreshing process. However, this may indicate that relatively fresher water is flushing the salty Dammam aquifers.

Figure 4.14 Maps showing the distribution of the major ionic ratios in the Khobar aquifer



(a) Na/Cl ratio

(b) SO4/Cl ratio

(c) Ca/Mg ratio

(d) Ca/Na ratio

Figures 4.15a through d display the distribution of the major ionic ratios in the Rus - Umm Er Radhuma aquifer. It can be seen that the distribution of the ionic ratios in this aquifer also shows a decrease in the NW-SE direction, but this trend appears to be less discernible in the case of the Na^+/Cl^- and Ca^{2+}/Na^+ ionic ratios. This possibly reflects the complexity within this aquifer already demonstrated on the piezometric and hydrochemistry grounds. It is possible that such distribution patterns are controlled mainly by gypsum/anhydrite dissolution, and by variation in ionic ratios due to the cation exchange and reverse exchange processes, and normal hydrochemical evolution.

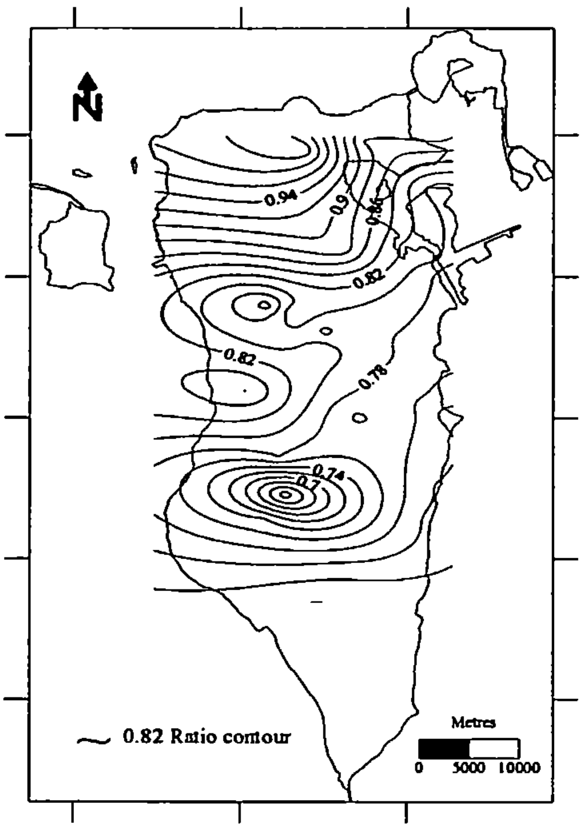
4.6 Chemical Speciation

Because carbonate rocks form the matrix of the aquifer systems in the study area, calculations of saturation state of specific minerals such as calcite, dolomite, and aragonite is of prime importance. The chemical analysis of water samples collected as part of this investigation (all the samples of the Alat Limestone and Rus - Umm Er Radhuma aquifers, and a random selection of 75 samples from the Khobar aquifer) were subjected to equilibrium speciation calculations to indicate state and degree of saturation with respect to some minerals using the computer speciation code WATEQ4F (Ball and Nordstorm, 1992). This includes calculation of saturation indices, equilibrium partial pressure of carbon dioxide (P_{CO_2}), and ionic strength (IS).

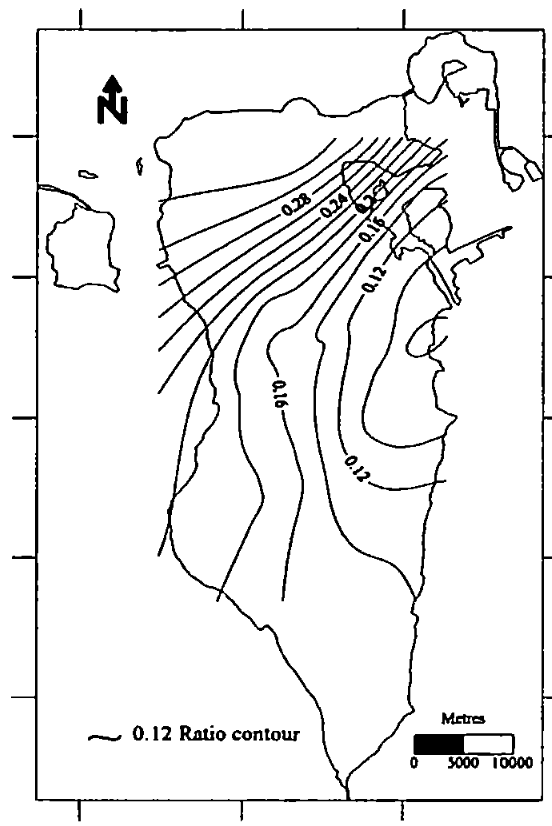
The saturation index for a particular mineral may be defined by the equation (Lloyd and Heathcote, 1985):

$$SI = log\left(\frac{IAP}{Ks}\right)$$

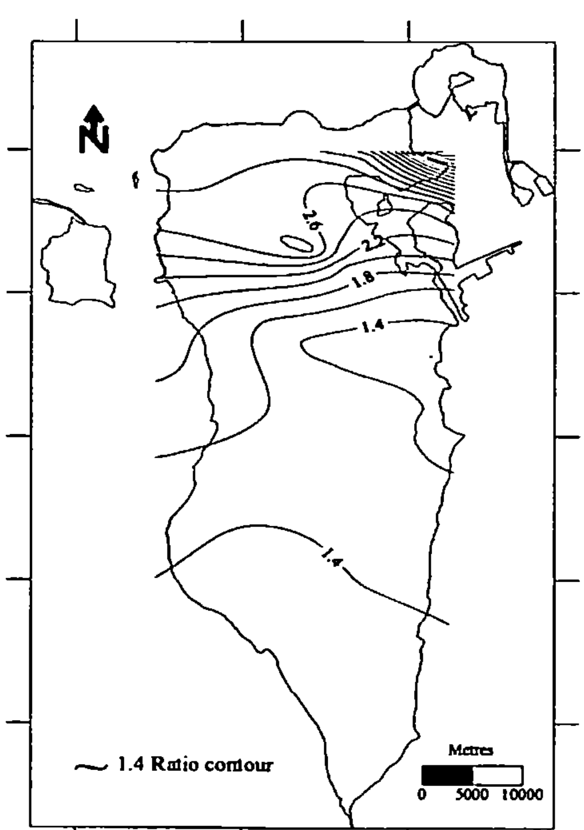
Figure 4.15 Maps showing the distribution of the major ionic ratios in the Rus - Umm Er Radhuma aquifer



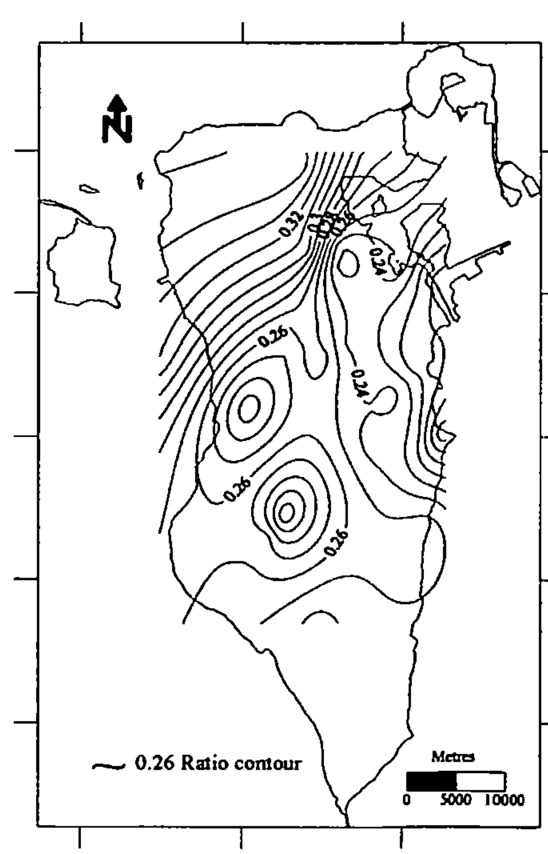
(a) Na/Cl ratio



(b) SO4/Cl ratio



(c) Ca/Mg ratio



(d) Ca/Na ratio

Where SI is the saturation index for a given mineral, IAP is the ionic activity product of the ions forming this mineral and K_S is the solubility product of the mineral at saturation. For example, the calcite saturation index SI_C is defined by:

$$SI_C = log \left\{ \frac{(Ca^{2+})\,(CO_3^{\ 2-})}{Ks_C} \right\}$$

Groundwater is in equilibrium with respect to a particular mineral when the saturation index equal zero, undersaturated when the index is negative, and oversaturated when the index is positive (Lloyd and Heathcote, 1985). An oversaturated state indicates that the mineral has a potential to precipitate from the solution. Undersaturation means that more of the mineral could be dissolved in the solution, while the equilibrium state indicates that the mineral would neither precipitate nor dissolve (Lloyd and Heathcote, 1985; Appelo and Postma, 1999).

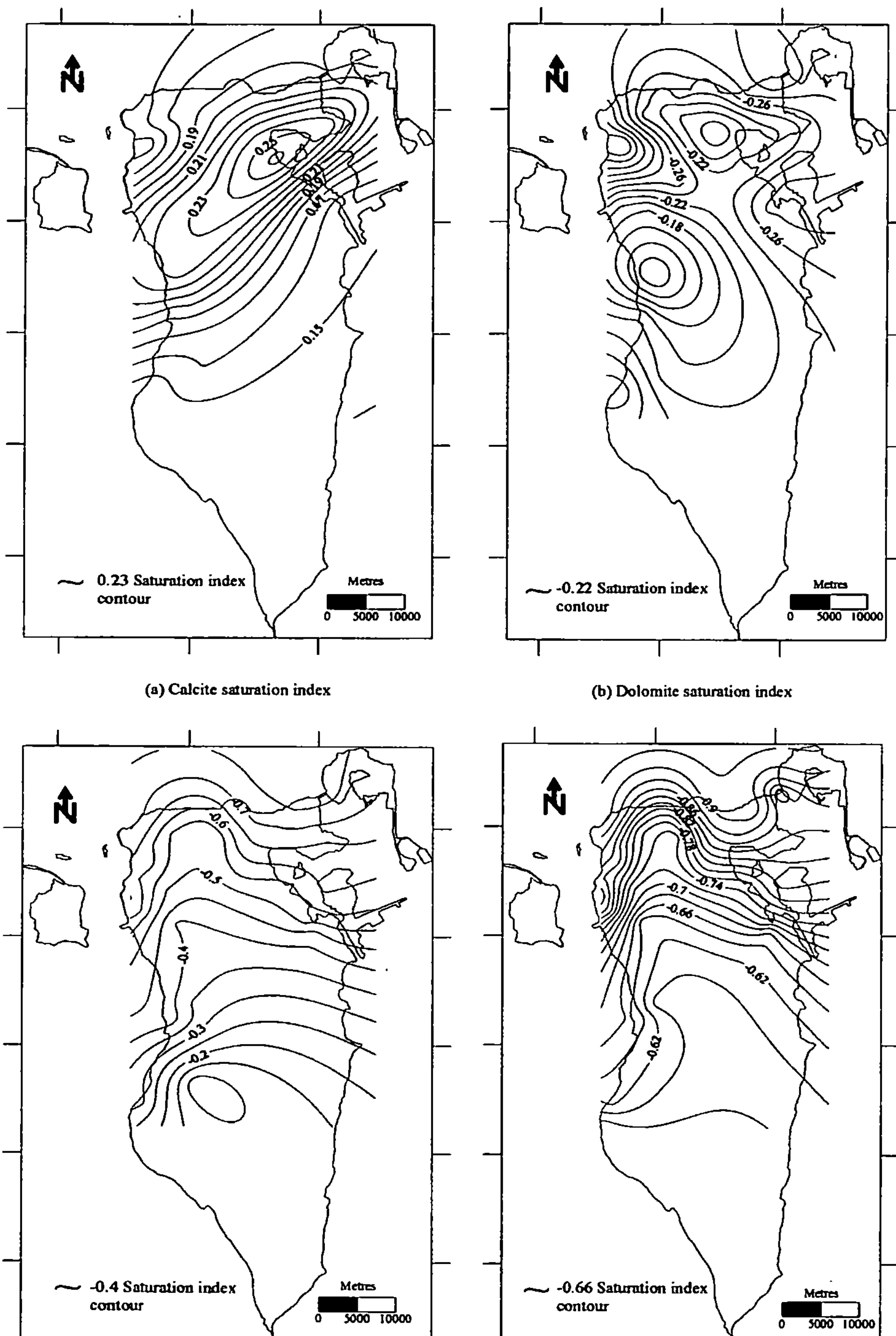
The saturation indices of groundwater samples from the Alat Limestone and Khobar aquifers, along with their calculated P_{CO_2} and ionic strength (IS) values are appended in Tables C-5 and C-6 of Appendix C, respectively. The results indicate that on average the Dammam groundwaters are undersaturated with respect to the anhydrite, dolomite, gypsum and halite, but are oversaturated with respect to the calcite and aragonite. The calculated P_{CO_2} for the Alat ranges between 1.65×10^{-3} and 1.49×10^{-1} atmosphere (atm), with a mean value of 1.73×10^{-2} atm. The ionic strength is from 0.0538 to 0.286, with an average value of 0.0867. The average P_{CO_2} value for the Khobar groundwater is found to be ranging from 9.69×10^{-3} to 1.01×10^{-2} atm; with a mean value of 1.62×10^{-2} atm. It follows that in both aquifers, the carbon dioxide pressure is above the atmospheric P_{CO_2} of

$10^{-3.5}$ atm; indicating that groundwater in the Dammam system is furnished with CO_2 during infiltration through soil zones. Table C-6 shows that the ionic strength of the Khobar samples ranges between 0.0535 and 0.266, and averaging at 0.106.

The distribution of saturation indices of the Khobar groundwater is shown in Figure 4.16. The maps in the figure demonstrate the saturation indices of calcite, dolomite, gypsum, and anhydrite. Figure 4.16a shows that the oversaturation with respect to calcite increases at the beginning but then decreases along the direction of the flow path. This can be explained by the cation exchange with sodium in the aquifer along the flow path. The degree of undersaturation state with respect to dolomite (Figure 4.16b) indicates increasing pattern towards the direction of groundwater flow, possibly reflecting dolomitisation process along this path. Figures 4.16c and d show that the degree of undersaturation of gypsum and anhydrite is increasing along the flow direction, indicating possible evaporite dissolution in this direction.

The saturation indices of the Rus - Umm Er Radhuma water samples, and the calculated P_{CO_2} and IS are tabulated in Appendix C, Table C-7. In general, the groundwater in this aquifer is undersaturated with respect to anhydrite, gypsum and halite, and is oversaturated with respect to aragonite, calcite, and dolomite. The oversaturation with respect to dolomite in the Rus - Umm Er Radhuma aquifer is consistent with the minerological composition of this aquifer in which the dolomitic limestone and dolomite form the major rock units; the undersaturation with respect to gypsum and anhydrite appears to be consistent with the traditional view of evaporites dissolution within the Rus section. The values of P_{CO_2} in the Rus - Umm Er Radhuma varied from 1.13×10^{-8} to 5.7×10^{-2} atm, with a mean value of 1.07×10^{-2}. The calculated ionic strength falls in the range 0.088

Figure 4.16 Saturation indices maps of the Khobar aquifer



(a) Calcite saturation index

(b) Dolomite saturation index

(c) Gypsum saturation index

(d) Anhydrite saturation index

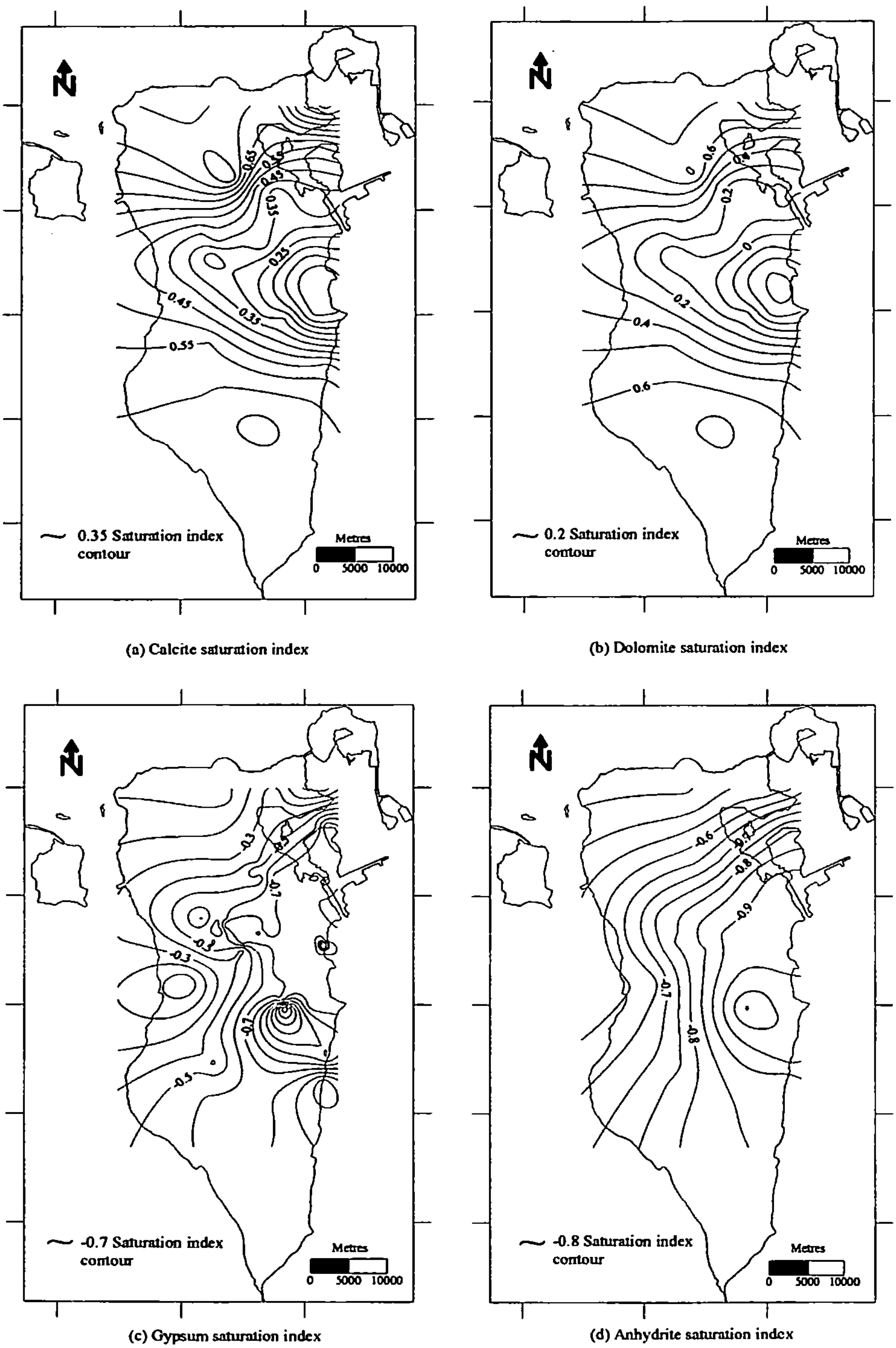
and 0.456, with an average value of 0.218.

The saturation indices maps of calcite, dolomite, gypsum, and anhydrite in the Rus - Umm Er Radhuma aquifer are illustrated in Figures 4.17a to 4.17d. Figures 4.17a and b show that the degrees of oversaturation with respect to calcite and dolomite generally decrease as water moves downgradient possibly as a result of dedolomitisation, but this pattern is locally disrupted and shows rather complex behaviour towards the southern area. The degrees of undersaturation with respect to gypsum and anhydrite (Figures 4.17c and d) contrast with those of the Dammam system as they exhibit decreasing trend along the NW-SE direction. This appears to concide with the zero anhydrite line assumption, which suggests that the amount of evaporites in the Rus aquitard diminishes to the east and south.

4.7 Springs Water Quality

The chemical compositions of the natural spring waters together with their mean values and ranges (minimum and maximum) are summarised in Appendix C, Table C-8. The long-term salinity variations of water from springs are given in Table 4.9. The data in the table indicate that all the springs have shown a significant salinity increase since the first survey of 1952, obviously in conformity with the overall and gradual deterioration in the Dammam groundwater quality. Most of the springs have exhibited considerable fluctuations in TDS levels, which may reflect seasonal patterns. These fluctuations are more noticeable in springs adjacent to the major pumping centres. It should be emphasised, however, that the 1952 data were computed from the salinity data given as NaCl using the conversion equation suggested by Italconsult (1971); the reliability of this equation can be seriously questioned. When compared with the results of the last spring

Figure 4.17 Saturation indices maps of the Rus-Umm Er Radhuma aquifer



(a) Calcite saturation index

(b) Dolomite saturation index

(c) Gypsum saturation index

(d) Anhydrite saturation index

Table 4.9 Salinity trends of water from Bahrain land springs 1952 – 1999

Spring name	Location	1952	1971	1979	1989	1991	1999
Al-Raha	Sitra	3147	7667(6)	7000(7)	5120	3840	8019
Muhazza	Sitra	3281	13974	---	---	---	---
Kathira	Sitra	13956	11227(6)	11510(7)	---	---	---
Adhari	Sehlat Al-Hadriyah	2946	2836	2750	4224	2933	5019
Al-Sayed	Tubli	3364	---	7040(8)	14850	---	---
Al-Sugra	Sanad	3415	3300	3400	6208	6720	9752
Al-Kubra	Sanad	3684	3700	4900	9152	7680	8877
Dabbasah	Nuwaidrat	3891	4500	---	10624	9280	48240
Umm Ash-Shaaum	Mahooz	2305	3100	2800	3251	2624	3878
Abu-Zaidan	Al-Khamis	2927	---	---	---	2304	---
Qasari	Al-Khamis	2952	---	3750	---	---	---
Al-Hakeem	Jurdab	3281	2900	2650	3968	---	4003

Table 4.9 (Continued)

Spring	Location	1952	1971	1979	1989	1991	1999
Al-Khadra	Aali	2671	---	13500[8]	11200	8960	---
Al-Safahiyah	Nabih Saleh	---	---	---	3264	2496	5264
Al-Shaikh	Nabih Saleh	---	---	---	3264	2752	8999
Ain Al-Jin	Karranah	---	---	4608[8]	4339	3456	5061
Ain Bashah	Tubli	3281	---	---	3460	3712	5177
Ain Abdan	Sitra	3220	---	---	---	---	---

SOURCE: Tabulated from data compiled from different sources.
All values are given as TDS in mg/l^{-1}. A dash indicates no data.
[1] 1952 data are derived from BAPCO files of salinity given as NaCl, using the formula developed by Italconsult (TDS = 1.22 x NaCl + 780).
[2] 1971 data from Italconsult.
[3] 1979 data are based on GDC (1980) analysis.
[4] 1989 data from Water Resources Directorate (1989).
[5] 1991 data are from Al-Noaimi (1993).
[6] date of 1972.
[7] data of 1977.
[8] data of 1982.

salinity survey (Al-Noaimi, 1993), it can be seen that all the springs have markedly deteriorated in quality between 1991/92 and 1997/98.

The decreasing salinity pattern of Al-Raha spring during the 1980s and 1990s is probably related to the overall improvement in groundwater quality in the Sitra area following major reduction in abstraction levels. The high salinity of the Kathira spring since the earliest survey may confirm its Rus Formation source as suggested by Steineke (1942). Most of the springs surveyed have shown decreasing trends from 1991 to 1998, perhaps in association with the relative reduction in municipal pumping in Manama and the eastern areas that allowed water levels, and hence salinity to decrease (Al-Noaimi, 1993). The introduction of some water conservation measures during that time has probably contributed to this improvement. The sudden salinity increase of Muhazza spring in the early 1970s can only be explained by saline invasion of seawater along the eastern coast in response to the localised large-scale abstraction at BAPCO refinery. The TDS concentration of Dabbasah spring peaked at 48,240 mg l^{-1} in 1998. This anomalously high TDS concentration could not be reasonably explained on hydrochemical or hydrological grounds. Such salinity, however, may represent a combination of modern seawater invasion and saline water from the Rus - Umm Er Radhuma aquifer. Laboratory analytical malfunction could also be a possible explanation. Re-sampling was not possible owing to the poor condition of the spring.

Springs are normally more vulnerable to contamination by coliform bacteria than groundwater. Table 4.10 compares the bacteriological quality results of this research work with those examined by Khunji *et al.* (1990). Unfortunately, *faecal coliforms* and *faecal Streptococci* determined in the previous study were not investigated here, because of the

Table 4.10 A comparison of bacteriological quality of water from land springs for the years 1990 and 1998

Spring	Khunji *et al.* (1990)		Present investigation (2004)	
	Total coliform	*E. Coli*	Total coliform	*E. Coli*
Adhari	4400	---	100	100
Al-Raha	1857	---	Nil	Nil
Umm Ash-Shaaum	51	---	Nil	Nil
Al-Shaikh	3450	---	Nil	Nil
Al-Sugra	2	---	Nil	Nil
Al-Kubra	175	---	18	18
Al-Jin	---	---	Nil	Nil
Dabbasah	3	---	9	Nil
Ain Bashah	---	---	---	Nil

Notes: [1] Data are expressed in number of colonies per 100 ml/sample.
[2] A dash indicates parameters not measured or spring not sampled.

lack in analytical facilities, whereas *E. Coli* tests were not performed in the previous study. The results, however, indicate that three springs were found positive with respect to coliform organisms, whilst seven of the springs sampled in 1998 were found contaminated with coliforms in 1990. In general, the table shows that springs were more contaminated in the previous study than in the present (1998) investigation. This is surprising in view of the progressive deterioration in the spring's conditions. It appears, however, that the abandonment of most springs between 1990 and 1998 consequent upon their deteriorating conditions is the most probable reason for such an improvement. Because the human and animal wastes were considered responsible for this contamination, according to Khunji *et al.* (1990), such abandonment would probably result in substantially less contamination.

The available springs salinity data are insufficient to describe the spatial distribution of their TDS concentration. These data, however, indicate that the springs' salinity distribution pattern seems to follow that of the Dammam groundwater, confirming the well-documented assertion that most of these springs originate from the Dammam aquifer system.

CHAPTER FIVE

NON-CONVENTIONAL WATER RESOURCES

It is apparent from the foregoing discussions of the groundwater situation in the study area that groundwater has undergone acute quantitative and qualitative exhaustion. The government has responded to this serious situation by embarking on an ambitious supply augmentation programme through a phased construction of large desalination and sewage treatment plants. The objectives of this programme are twofold: (i) to provide domestic water that meets international potable water quality standards, and (ii) to provide additional sources of water for agricultural and landscaping purposes in order to alleviate pressures on the Dammam groundwater and retain it for blending and other priority uses.

In this chapter, desalinated water and TSE will be assessed in terms of their availability and techno-economical, environmental, quality, social, health risk, and institutional constraints associated with their development. The chapter also attempts to evaluate agricultural drainage water quantitatively and qualitatively, again with emphasis on the various constraints facing its potential use.

5.1 Desalinated Water

Up to the year 1975, Bahrain was totally dependent on groundwater resources to meet the demand of all users. Realising the magnitude of the groundwater shortage and continuous deterioration in its quality, especially in the early 1970s, and the need to provide drinking water of requisite quality, the government embarked on a major desalination programme to supplement the groundwater supplies. In 1976, a dual-purpose seawater steam turbine/multistage flash (MSF) plant consisting of two 2.5 million gallons per day (mgd) (11,363.6 m^3 day^{-1} or 4.2 Mm^3 $year^{-1}$) units was constructed as part of the Sitra Power and Water Station Project. This was followed between August 1984 and May 1985 by a major expansion in this project, in which three additional distillers each rated at 5 mgd (22,727.3 m^3 day^{-1} or 8.3 Mm^3 $year^{-1}$) were commissioned. By the end of 1985, another independent 5 mgd desalination unit was added under the Abu Dhabi project to raise the station production capacity to 25 mgd (113,636.4 m^3 day^{-1} or 41.5 Mm^3 $year^{-1}$).

A 10 mgd (45,454.5 m^3 day^{-1} or 16.6 Mm^3 $year^{-1}$) brackish groundwater reverse osmosis (RO) plant was designed and built at Ras Abu-Jarjur in the eastern coast, and become operational in October 1984. The plant was originally built to produce drinking water of less than 500 mg l^{-1} dissolved solids at 65% recovery ratio. The operational recovery of this plant was increased in 1998 to 68% by adding one RO train, thus increasing its maximum throughput from 10 mgd to about 13.5 mgd (61,363.6 m^3 day^{-1} or 22.4 Mm^3 $year^{-1}$) (Burashid and Al-Mansour, 1999). Another reverse osmosis plant, using seawater as a source, was commissioned in 1990 in Ad-Dur (also in the eastern coast), with a reported production capacity of another 10 mgd (16.6 Mm^3 $year^{-1}$). However, owing to problems in the pre-treatment facilities, full plant production has never been achieved and since commissioning, output ranges between 1 - 6 mgd. A pre-treatment system rehabilitation programme is currently being undertaken in order to achieve the designed plant capacity of 10 mgd.

The first phase of Hidd Power and Water Plant was designed to produce 30 mgd (136,363.6 m^3 day^{-1} or 49.8 Mm^3 $year^{-1}$), and was commissioned in September 1999. This has raised the total installed desalination capacity, assuming that Ad-Dur rehabilitation programme is completed successfully and the plant is producing at its designed output, to 78.5 mgd (356,818.2 $m^3\,day^{-1}$ or 130.3 $Mm^3\,year^{-1}$). Upon completion of phase two of this Plant, which is re-planned to be operational beyond the year 2006, an additional 30 mgd of desalinated water would be available for use.

Alba Coke Calcining/Desalination Plant is presently underway and is expected to be operational by mid 2004, with a planned capacity of 9 mgd (40,909.1 $m^3\,day^{-1}$ or 14.9 $Mm^3\,year^{-1}$). This means that the total availability of desalinated water would be 87.5 mgd (397,727.3 $m^3\,day^{-1}$ or 145.2 $Mm^3\,year^{-1}$) by no later than 2004, again provided that Ad-Dur is achieved its planned output level. By nearly the end of 2006, when the Hidd Phase II expansion is implemented, the total installed desalination capacity would be at 117.5 mgd (534,090.9 $m^3\,day^{-1}$ or 195.0 $Mm^3\,year^{-1}$). The existing and proposed desalination plants and their production capacities are summarised in Table 5.1.

In addition to these major desalination plants, there are many small private electrodialyses and reverse osmosis units, which desalinate groundwater both from Dammam and Rus - Umm Er Radhuma aquifer systems. These are primarily used to supply some industries, hotels, housing compounds, and non-productive agriculture (sports field and golf course irrigation) with their water requirements. The total capacity of these private desalination facilities is estimated by Mott MacDonald (1997) at about 64,000 m^3/day (14 mgd). Updated figures on this total are not available.

As indicated earlier, the desalination programme has not been planned merely to supplement the groundwater supply, but also to provide domestic water of appropriate quality that meets the international standards (i.e. total dissolved solids content not

Table 5.1 The existing and proposed desalination plants and their annual production capacities

Desalination plant	Type of desalination	Production capacity (Mm^3/year)
Existing plants		
Sitra Power and Water Station	Multistage flash	41.5
Ras Abu-Jarjur Desalination Plant	Brackish groundwater reverse osmosis	22.4
Ad - Dur Desalination Plant	Seawater reverse osmosis	16.6*
Hidd Power and Water Plant (Phase I)	Multistage flash	49.8
Total existing output		130.3
Proposed plants		
Alba Coke Calcining Desalination Plant	Multistage flash	14.9
Hidd Power and Water Plant (Phase II)	Multistage flash	49.8
Total output in approximately 2006		195.0

* Assuming full output.

exceeding 1,000 mg l^{-1}), with costs of distillate production and distribution always in mind. In order to achieve these objectives, a blended supply policy is therefore adopted by which the produced desalinated water is blended with groundwater in about 1:1 ratio before being supplied to the consumers. With the commissioning of Hidd phase one distillate, the blending ratio has been improved to 3:1.

5.1.1 Blended Water Quality

The blended water quality for selected years is given in Table 5.2. The table clearly shows that in the early stages when the distillate output was relatively sufficient, the average blended water quality was below the desired level of 1,000 mg l^{-1} TDS. However, at some later stages, when the desalination output falls short of the actual water demand, particularly during the peak periods, the blending ratios had to be adjusted, resulting in higher TDS levels, although the initiation of a daily consumption ceiling programme of 70 mgd (318,181.8 m^3 day^{-1}) since 1994 has somewhat curtailed this deterioration. The situation has improved significantly with the introduction of the Hidd distillate during the year 2000. Obviously, when the Alba Coke Plant and the planned expansion at Hidd are implemented, the quality of the blended supplies would be further improved.

The chemical analysis results of the blended water from the various blending stations as of December 2000, along with the quality standards for drinking water developed by the World Health Organisation (WHO, 1993) and the Gulf Co-operation Council (GCC, 1994) are given in Table 5.3. The data in the table indicate that the TDS concentration in most of the blending stations varies from 660 to 985 mg l^{-1}, while the maximum recommended limit in both guidelines is 1,000 mg l^{-1}. The exceptions are in Hamad Town and West Riffa blending stations, where the TDS levels reach 1,365 and 1,200 mg l^{-1}, respectively.

These stations are located at relatively higher elevations and due to the pumping limitation at Hidd plant, shortage in desalinated supply is common, giving rise to the TDS values because of the necessary adjustments in blending ratios.

Table 5.2 Blended water quality from the various blending stations (TDS mg l^{-1})

Blended Station	1985	1990	1995	2000*
Hamad Town	540	1190	1280	1100
Hidd	1010	1300	1830	720
Hoora	670	1110	1575	760
Mahooz	670	800	1375	765
Muharraq	1010	1300	2210	710
Musalla	670	1130	1620	720
Salmaniya	670	1130	1660	780
Sitra	725	930	945	835
West Riffa	540	980	1180	1145
Annual average	723	1097	1519	837

SOURCE: Tabulated from data made available by the Ministry of Electricity and Water.
* After the introduction of Hidd distillate.

The pH values in the blended water are slightly higher than the values in groundwater. It seems that the chemical compounds usually added during the desalination process to neutralise the carbon dioxide and to control the pH are responsible for this increase. However, the pH concentrations found in blended water are within the range of acceptability. The only exception is at Sitra Blending Station, which has a pH concentration greater than the maximum allowable limit. Hardness in blended water varies from 159 to 451 mg l^{-1}, which is below the permissible levels of the GCC guidelines and the taste threshold limit of the WHO (both set at 500 mg l^{-1}). Chloride concentrations in the blended water are considerably higher than the upper limit values in the two

Table 5.3 Chemical analysis results of blended water as of December 2000, along with the World Health Organisation (WHO) guideline values and the Gulf Co-operation Council (GCC) standard limits for drinking water

Blended Station	E.Cond (μS/cm)	TDS	Alkalinity	Hardness	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	F	NO_3^{-}
Sa'ar Tower	1170	660	43	216	8.27	51	22	145	8	**267**	99	52	---	---
Sitra	1260	680	21	159	**8.99**	24	24	188	7	**343**	48	26	**0.07**	6.1
Hamad Town	2310	**1365**	79	451	8.45	108	44	**296**	16	**534**	250	96	**0.27**	13.5
West Riffa	2090	**1200**	66	404	7.82	98	39	**262**	14	**456**	232	81	**0.21**	11.2
Sanabis	1350	805	43	282	7.73	64	30	180	10	**380**	85	53	**0.44**	17.5
Musallah	1340	790	43	333	7.86	67	40	150	12	**337**	110	53	**0.42**	17.5
Sulmania	1580	960	67	390	7.61	85	43	185	12	**400**	150	82	**0.36**	15.3
Mahooz	1860	985	24	227	8.25	56	21	**275**	10	**500**	88	29	**0.08**	7.7
Hoora	1600	890	44	284	7.66	57	34	**207**	9	**389**	120	54	**0.38**	18.5
Hidd	1260	700	40	233	7.80	55	23	150	9	**289**	103	49	**0.48**	21.3
Muharraq "C"	1200	680	43	232	7.39	58	21	145	7	**280**	100	52	**0.46**	18.8
Janusan Tower	1215	685	45	224	8.23	52	23	148	9	**281**	99	55	---	---
WHO (1993) Guidelines	NSS	1000	NSS	NSS	6.5 – 8.5	NSS	NSS	200	NSS	250	250	NSS	1.5	50
GCC (1994) Standard Limits	NSS	1000	NSS	500	6.5 – 8.5	200	150*	200	NSS	250	400	NSS	0.6 – 1.7	<1

SOURCE: Tabulated from data made available by Ministry of Electricity and Water.
All values are given in mg l^{-1}, except where indicated. pH in pH unit. Fluoride (F) values are as of January 2000, and Nitrate (NO^{3-}) values are as of February 2000. Alkalinity and Hardness are as $CaCO_3$. NSS indicates no standard limits set. * Magnesium concentrations should not be greater than 30 mgl^{-1} when the sulphate concentrations ≥ 250 mgl^{-1}. Values above or below the recommended limits are given in bold face.

guidelines, while the sulphate contents are within the recommended maximum levels. No guideline values have been proposed for the bicarbonate, but concentrations in the range of 26 – 82 mg l^{-1} of this constituent may be regarded as quite acceptable.

About 67 % of the water samples have concentrations lower than the maximum allowable limits with respect to sodium. Concentrations in excess of the guideline values at Hamad Town and West Riffa Blending Stations are most probably attributed to the shortage in desalinated supply referred to earlier. All the blended stations have calcium and magnesium concentrations markedly lower than the recommended limits of 200 and 150 mg l^{-1}, respectively, recommended in the GCC drinking water quality standards. The WHO does not specify guideline values for these parameters.

The above inorganic constituents in drinking water are not of immediate health relevance (aesthetics-related), but at certain levels may be objectionable to consumers for various reasons and thus, no health-based guideline values have been proposed for these constituents (WHO, 1993). The most important inorganic substances in drinking water in terms of potential health effects are the fluoride and nitrates as NO_3^-. Excess or shortfall in fluoride is associated with dental caries and bone problems such as dental fluorosis and skeletal fluorosis, and possibly kidney damage, whereas excessive exposure to nitrate can cause several health problems.

As it the case with the boron in irrigation water, fluoride concentration in drinking water is very sensitive. Generally, fluoride levels in drinking water should not exceed 1.5 mg l^{-1}, but a minimum concentration of 0.6 mg l^{-1} has to be maintained. Optimum fluoride level in drinking water in Bahrain is placed at 0.6 – 0.7 mg l^{-1} (Ministry of Health, 1986, cited in

Al-Awadhi and Jose, 1989). The fluoride levels in the blended water range between 0.07 and 0.48 mg l^{-1}, with an average of 0.32 mg l^{-1} (Table 5.3). These concentrations are considered extremely low and, unless fluoride deficiency is supplemented from some other sources, such a fluoride level may be a health hazard. An artificial fluoridation programme has been proposed at various times, but has yet to be implemented. With the continuous progress in the desalination output, a drinking water fluoridation programme that takes into account the climatic conditions, common fluoride intake volumes, and intake from other sources must be considered as one of the major policy issues.

The international health-based drinking water quality guidelines include a maximum concentration of 50 mg l^{-1} nitrate. The data in table 5.3 show blended water containing nitrate concentrations ranging from 6.1 to 21.3 mg l^{-1}, with an average value of 14.8 mg l^{-1}. This range is consistent with the nitrate levels (as only NO_3^-) commonly found in groundwater that might be used for domestic purposes (see Tables C-1 and C-2 of Appendix C). The nitrate concentrations in blended water fall below the maximum permissible level set in the WHO guidelines. The maximum limit for nitrate suggested by the GCC standards is considered impractically stringent. From the preceding discussion, it may be concluded that, apart from the fluoride problem in all the blending stations and the elevated TDS concentrations at Hamad Town and West Riffa stations, the blended water quality is suitable for drinking purposes.

5.1.2 Desalination Cost

Desalination requires substantial capital investment. When planning for distillate requirements to meet the municipal demands, the economic evaluation in terms of unit cost of water produced should be carefully considered. The unit production cost at any desalination plant depends mainly on the desalination process employed and the plant operational availability. The cost of producing one m^3 of distillate water at the dual purpose Sitra Power and Water Station for the last six years (1995 – 2000) varies from BD 0.179/m^3 to BD 0.228/m^3 and averaged at BD 0.216/m^3 (US$ 0.57/m^3) (K. Burashid, Ministry of Electricity and Water, written communication).

At the Ras Abu-Jarjur single purpose Reverse Osmosis Plant, which uses brackish water from the Rus - Umm Er Radhuma aquifer as a source, the unit water cost ranges over the same period from BD 0.223/m^3 to BD 0.269/m^3, giving an average unit cost of BD 0.243/m^3 (US$ 0.64/m^3). It follows that the average unit cost from both the multi-stage flash and reverse osmosis plants is around BD 0.230/m^3 (US$ 0.61/m^3) (K. Burashid, Ministry of Electricity and Water, written communication). It should be emphasised here that the above estimates are based on the current energy price of about US$ 0.25 per Million British Thermal Unit (MBTU). Therefore, if the market energy cost of about US$ 1.0/MBTU were taken into account, the unit production cost would certainly be appreciably higher.

The transmission and distribution costs are estimated at BD 0.140/m^3 or US$ 0.37 (Al-Mansour, 1999). Therefore, the total cost of producing, transmitting, and distributing of one unit of desalinated water is estimated at about BD 0.370/m^3 (US$ 0.98/m^3). Owing to the operational problems currently being encountered at the Ad-Dur Seawater Reverse Osmosis Plant, the unit cost at this plant is obviously higher. At lower recoveries of between 30% to 33%, the unit cost is estimated at approximately BD 0.405/m^3 (US$ 1.1/m^3) (M. Al-Ansari, Bahrain Centre for Studies and Research, personal communication). It is hoped, however, that the rehabilitation programme presently being undertaken would result in lower unit cost.

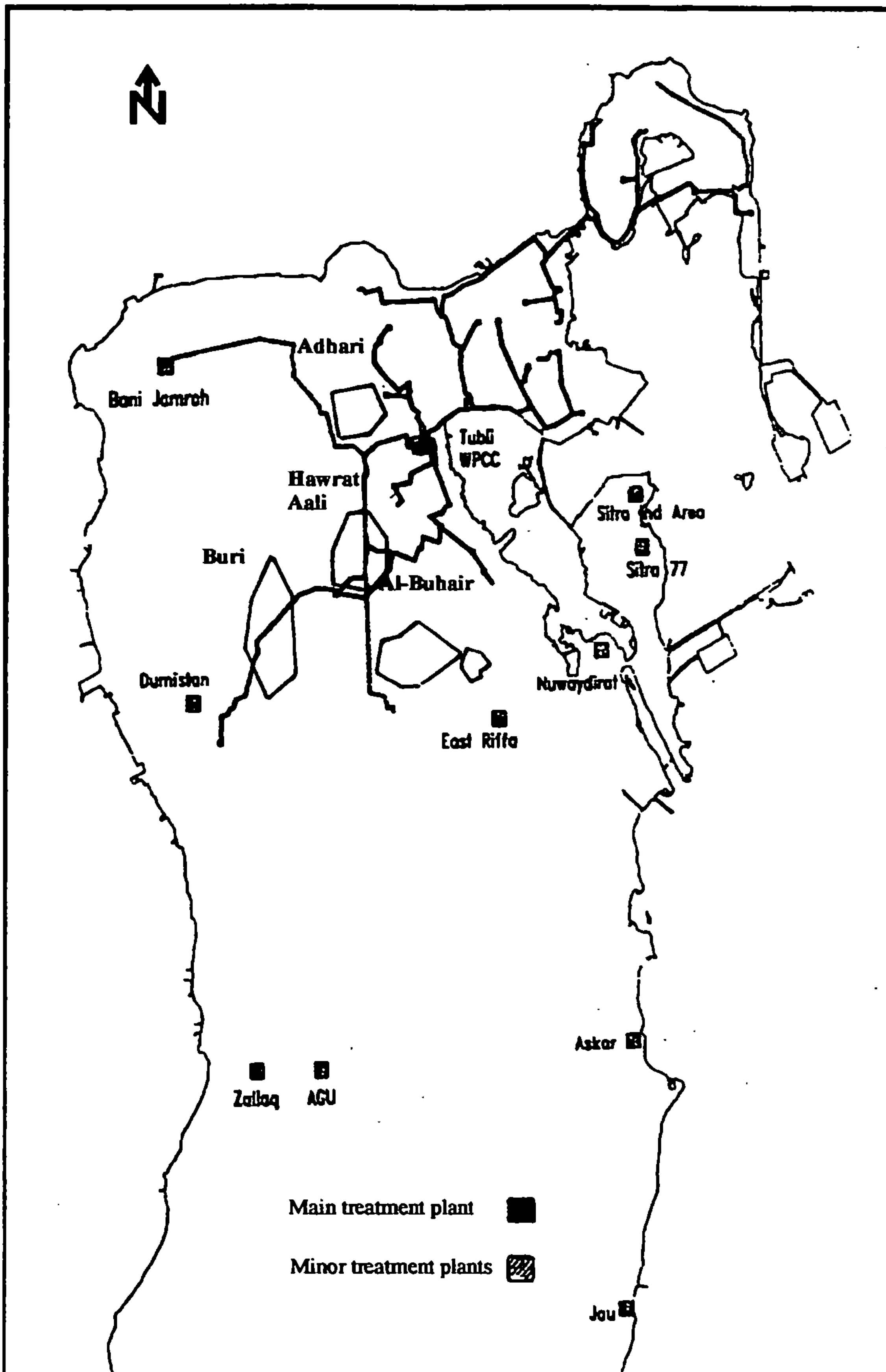
5.2 Treated Sewage Effluent

In 1975, J. D. and D. M. Watson Consulting Engineers completed a master plan study to investigate the current and future needs for sewerage and sewage treatment for Bahrain Metropolitan Area (Charlesworth and Al-Aradi, 1992). Construction of trunk sewers and main pumping stations was completed between 1977 and 1979. So far (2001), about 70 % of secondary sewers, drainage lines and house connections within the existing treatment plant watershed have been completed. It is expected that by the year 2015, the whole of the inhabited part of Bahrain will have sewers (Al-Aradi and Burashid, 1997).

The main wastewater treatment plant in the study area is the Tubli Water Pollution Control Centre (Tubli WPCC), which is located at a reclaimed area adjacent to the Tubli Bay. There are eleven minor treatment plants, with a total designed capacity of about 9,720 m^3 day^{-1}. The plants with the largest capacities are the South Alba, North Sitra, Nuwaidrat, and Jaw treatment plants. The locations of the existing main and minor treatment plants are shown in Figure 5.1. Also included in the figure are the locations of the agricultural areas currently being supplied by TSE.

The treatment works at Tubli were designed by the Associated Consulting Engineers (ACE), and construction commenced in 1979, and commissioned in August 1982. The potentials for re-use of TSE for irrigation and other non-potable purposes as well as sludge and compost for land fertility improvement were considered in further details by ACE in 1984. The Consultants' report concludes that, with careful planning and proper management, the TSE will be a valuable source of irrigation water at relatively low cost.

Figure 5.1 Location map showing the Tubli WPCC, the minor wastewater treatment facilities, and the agricultural areas irrigated by TSE (adapted after Tubli WPCC Authority)



The report also states that the quantity and quality of the sewage sludge justify its use as an efficient soil conditioner. The re-use of the TSE for irrigation purposes under the TSE Production and Utilisation Project Phase I was began late in 1984. The proposed development under phase II is now underway and is expected to be operational by the year 2004.

The existing wastewater treatment facilities at Tubli WPCC include screening and grit removal for primary treatment; an extended aeration activated sludge process, and settling by clarifiers as secondary biological treatment; and dual-medium filtration, pre-chlorination, disinfection by ozone followed by post-chlorination for tertiary treatment. The ozonation facility was added to the system in 1987 to ensure high standard treated effluent. The ozone dosage used for the basis of design is about 7 - 10 mg l^{-1}, while the residual chlorine is at around 1.5 mg l^{-1}. The sludge treatment facilities consist of two gravity thickeners and seventy-two sludge- drying beds (PES, 1995).

The Tubli Plant is currently producing about 160,000 m^3 day^{-1} of secondary treated effluent. Out of this amount, around 41,000 m^3 day^{-1} receives tertiary treatment and is re-used for agriculture and landscape irrigation. At present (2001), about 34,000 m^3 day^{-1} of high quality tertiary treated effluent is being utilised for productive agriculture, and some 7,000 m^3 day^{-1} is used by the Central Municipal Council (CMC) for landscape irrigation and roadside planting. The balance of about 119,000 m^3 day^{-1} of secondary effluent is dumped to the sea.

The tertiary treated effluent is pumped from the post-chlorination contact tank through transmission lines to five storage reservoirs, with a combined storage capacity of

20,000 m^3. It is then distributed to three governmentally owned agricultural projects in Adhari, Hawrat Aali, and Buhair areas; in addition to some 94 private farms in the Buri area (see Figure 5.1). Sewage sludge and compost of approximately 20 tons per day is stockpiled in Tubli for 6 to 12 months before being used as fertilizer (A. Al-Aradi, Tubli WPCC, personal communication).

The design capacity of the tertiary treatment under Phase I is about 60,000 m^3 day^{-1}, based on 24 hour per day operation, and assuming an average secondary effluent flow of 124,000 m^3 day^{-1} and a peak flow of about 140,000 m^3 day^{-1}. This capacity is governed by the available pumping capacity and the ozone generation capacity, but the ozonation contact tank was designed to allow for an ultimate treatment capacity of about 140,000 m^3 day^{-1}.

The actual TSE production, as indicated earlier, is currently limited to 41,000 m^3 day^{-1}. This quantity is insufficient to meet even the current agricultural water needs. The poor quality of the secondary effluent during peak flow and the inefficiency of the secondary filters and clarifiers are the major factors for the inability of the tertiary treatment system to produce at its design level (PES, 1995). According to the same source, design, construction, and operation and maintenance problems as well as lack in storage capacity are also contributing to the failure in achieving full TSE utilisation.

The overloading of the secondary effluent and failure of filters have resulted in inadequate removal of parasites (Strongyloides Stercaralis) larvae. These organisms pass through the filters to the tertiary treatment system and tend to multiply within the filters and transmission lines (Gur, 1991). In the previous years, several remedial measures were proposed by some investigators (Gur, 1991; PES, 1995; Pescod, 1996) to resolve the problem of parasites surviving all the treatment processes. This problem has been partially overcome by taking a major step to improve the filter's efficiency, and by increasing the chlorine and ozone dosages, but complete parasite removal is yet to be achieved, mainly because of the continuous overloading at the collection system and secondary treatment facilities.

The initial stage under phase II of the project assumes full (60,000 m^3 day^{-1}) utilisation of TSE. By the year 2007, and as part of the proposed Phase II development, the Tubli Plant is envisaged ultimately to produce about 200,000 m^3 day^{-1} (73 Mm^3 $year^{-1}$). Beyond this date, further expansion at Tubli or construction of another treatment plant is essential (ACE - Al-Moayed, 1997). The available quantity at the initial stage of the current phase is expected to irrigate an area of about 630 hectares (ha), mainly of fodder crops. Most of the TSE under Phase II extension will be required to irrigate the existing agricultural areas in the west coast and some reclaimed areas in the north-central region.

The additional areas planned to receive tertiary treated effluent within Phase II programme, including landscaped urban areas is estimated at about 2,400 ha. In conditions of high summer demands, the irrigation water requirements for these areas are estimated at 270,000 m^3 day^{-1}. The deficit in irrigation demands is to be met by a series of emergency wells connected to the distribution system (ACE- Al-Moayed, 1997). These wells will also be required in cases of maintenance or plant shutdowns. On the other hand, the surplus quantity in times of low irrigation demands was envisaged to be used for possible artificial groundwater recharge. Sewage sludge quantity at the ultimate stage is expected to increase to about 38 tonnes per day, associated with some improvements in sludge treatment facilities (ACE - Al-Moayed, 1997).

5.2.1 Wastewater Flows

Presently, the Tubli works serve a population of approximately 540,000; the population within the Tubli watershed is anticipated to reach around 720,000 when Phase II extension comes on stream. ACE (1984) estimated the total wastewater flows to the Tubli WPCC at approximately 92,000 and 130,000 m^3 day^{-1} in the years 1990 and 2000, respectively. The average wastewater flow entering Tubli is projected to reach about 145,000 m^3 day^{-1} in 2005 and 159,000 m^3 day^{-1} by the year 2010. These projections have been calculated based on a per capita contribution to wastewater flow of 227 litre day^{-1}, and infiltration and excess overflow allowances of 45 litre day^{-1}.

Records of flows at Tubli indicate that the actual wastewater flows are in excess of the projected ones by about 20 %. The reasons for this difference are the higher population growth and possibly inaccurate estimates of infiltration from drainage lines connections. Consequently, these projections were revised by ACE (1989) based on the modified population forecast and further adjustments to the uncontrolled discharge to the wastewater collection system. The initial and revised estimates of average daily flows are given in Table 5.4

The minimum and maximum daily wastewater flows to the Tubli WPCC for the year 2000 are estimated at about 139,396 and 179,660 m^3 day^{-1}, respectively, with an average daily flow of around 159,595 m^3 day^{-1}. These values indicate that the minimum daily flow is about 87 % of the average flow, and that the maximum flow is only 11 % higher than the average. Such flow analysis is of prime importance for evaluating the plant design,

Table 5.4 The initial and revised estimates of the average daily wastewater flows to the Tubli WPCC

	Average daily wastewater flows ($m^3 day^{-1}$)	
	Initial estimates ACE (1984)	Revised estimates ACE (1989)
1990	92,000	110,000
1995	112,000	132,000
2000	130,000	145,000
2005	145,000	160,000
2010	159,000	195,775*

*Not given in the original flow forecasts; projected by ACE - Al-Moayed (1997).

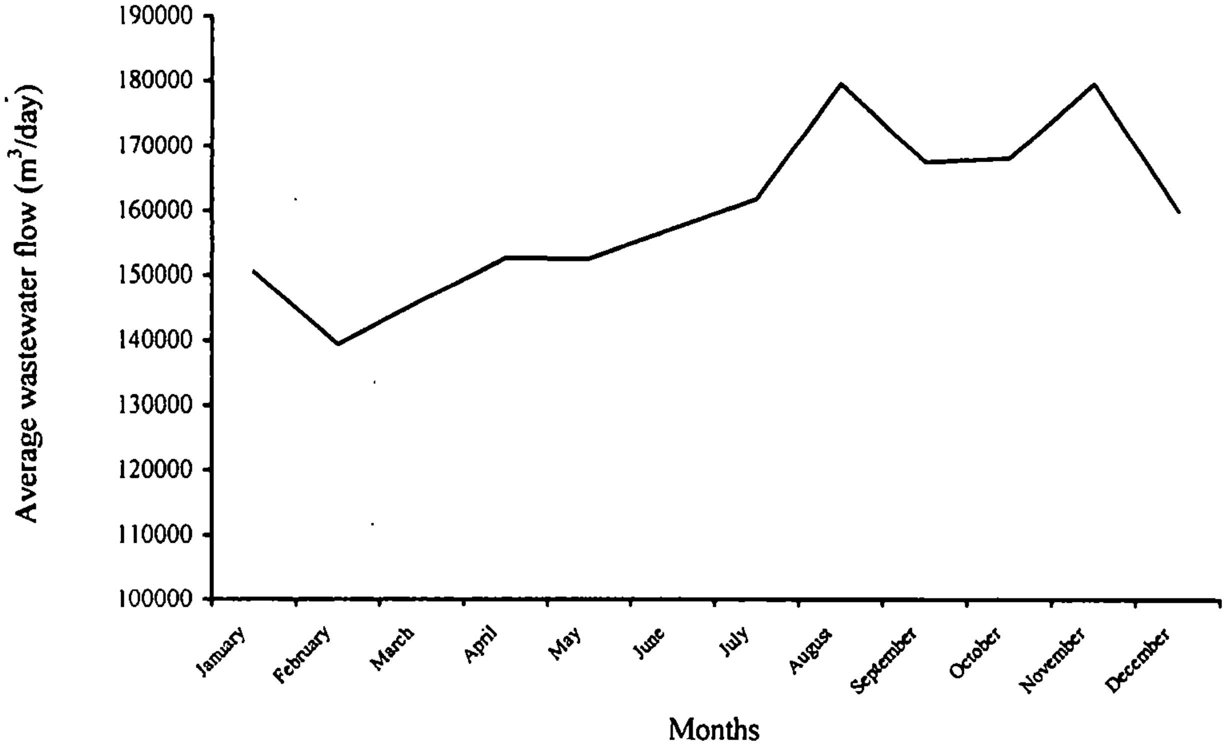
possible need for in-plant storage facility, and the quantity of wastewater available for reuse. The monthly fluctuations in raw wastewater flows observed for the period January - December 2000 are given in Figure 5.2. As previously stated, out of the average daily wastewater flows to the Tubli Plant, about 26 % (41,000 m^3) receives tertiary treatment and become available for recycling. The remaining quantity of about 119,000 m^3 (equivalent to 74 %) is discharged into the sea after being treated secondarily in order to comply with the wastes disposal regulations set by the environmental protection authority.

5.2.2 Wastewater Quality

When considering the reuse of treated sewage effluents for irrigation, their inorganic, organic, and microbial properties have to be carefully assessed and compared with the recommended standards to ensure safe use. The primary objective is to produce effluents that meet these standards, although local specific conditions must be taken into consideration. This is also applicable when treated wastewater is intended for reuse as a source for groundwater recharge.

Months	Average flow (m^3/day)
January	150,522
February	139,396
March	146,131
April	152,584
May	152,533
June	157,191
July	161,808
August	179,660
September	167,541
October	168,145
November	179,625
December	160,000
Average flow	159,595

Figure 5.2 Monthly fluctuations of wastewater flow to the Tubli WPCC for the year 2000



A summary of the raw wastewater quality, which represents monthly averages over the period January - December 2000 is presented in Table 5.5. The table gives average concentrations of 275, 226, and 22 mg l^{-1} for the TSS, BOD, and ammonia-nitrogen as NH_3-N, respectively. The BOD value is well below the recommended maximum concentrations of 250 mg l^{-1}, whilst the average TSS shows concentration of slightly higher than the recommended limit of again 250 mg l^{-1}. The average ammonia-nitrogen value is within the maximum recommended level of 25 mg l^{-1}. The increase in the suspended solids content is most probably due to overloading at the collection systems. The total dissolved solids concentration of the raw wastewater reaching Tubli is averaging at about 3,215 mg l^{-1} (calculated from the average electrical conductivity value multiplied by a factor of 0.64 obtained from Figure 4.3, Chapter Three). This high total dissolved solids content closely reflects the raw wastewater municipal and domestic origins, and is also partially attributed to the infiltration from groundwater and perhaps seawater into the sewerage lines.

The monthly average analysis of the secondary effluent for the same period is summarised in Table 5.6. The average BOD is about 8 mg l^{-1}, which is well below the maximum acceptable limit of 20 mg l^{-1}, whilst the average total suspended solids is significantly higher than the recommended limit of 20 – 25 mg l^{-1}. It is to be mentioned here that before the overloading has become a major problem at Tubli WPCC, the TSS contents were below 150 and 15 mg l^{-1} in the raw wastewater and secondary effluent, respectively. Ammonia-nitrogen content is averaging at 1.8 mg l^{-1} against a maximum recommended concentration of 10 mg l^{-1}. Because of the biological process employed at Tubli Plant, the total solids concentration remains high with an average value of slightly higher than that of the raw wastewater.

Table 5.5 Monthly average analysis of the raw wastewater from Tubli WPCC January – December 2000

Months	Temp. (°C)	H_2S	pH (pH unit)	E.Cond. (μSm^{-1})	TSS	VSS	COD	BOD	NH_3-N
January	26	9.0	7.1	5458	288	220	609	232	23
February	26	8.9	7.2	5781	277	216	564	219	23
March	27	8.0	7.2	5771	269	217	589	240	21
April	30	9.4	7.2	5430	281	226	469	239	21
May	31	14.2	7.0	4900	268	224	532	221	22
June	32	23.7	7.0	4750	259	211	500	176	16
July	34	16.9	7.1	4823	265	203	493	230	24
August	35	47.0	7.1	5100	399	228	620	324	30
September	33	17.1	7.1	4670	280	211	496	251	21
October	32	11.5	7.0	4874	253	206	574	215	25
November	29	7.2	7.0	4177	234	165	435	184	19
December	28	5.4	7.1	4555	231	180	436	182	19

SOURCE: Tubli WPCC

Notes: TSS and VSS are appreviations for total suspended solids and volatile suspended solids.
All values are given in milligram per litre (mg l^{-1}) except where indicated.

Table 5.6 Monthly average analysis of the secondary treated effluent from Tubli WPCC January – December 2000

Months	Temp (° C)	pH (pH unit)	E.Cond. (µSm^{-1})	TSS	VSS	COD	BOD	NH_3-N
January	24.1	7.3	5703	184	144	47	13	1.0
February	23.7	7.3	5981	437	279	67	12	3.0
March	24.9	7.2	6000	321	224	55	27	1.7
April	27.6	7.3	5523	177	130	40	7	1.5
May	28.6	7.1	4987	107	67	34	3	1.4
June	29.6	7.1	4810	160	117	33	3	1.0
July	31.8	7.1	4677	174	131	31	2	1.5
August	33.3	7.2	5000	950	712	50	6	6.0
September	31.0	7.1	4777	318	215	34	5	0.5
October	29.9	7.1	4839	220	145	47	4	2.3
November	26.9	7.2	4530	165	97	40	7	0.9
December	25.6	7.5	4981	159	109	44	5	0.7

SOURCE: Tubli WPCC

Notes: TSS = Total Suspended Solid. VSS = Volatile suspended solids.
All values are given in mg l^{-1}, except where indicated.

Recent parasite analyses were not available for this study. Plant officials at Tubli, however, stated that *Strongyloides Stercaralis and Ascaris* in particular, are still surviving all the treatment processes employed in the system. Apparently, the proposed improvements in the sewerage collection system and treatment facilities as part of Phase II extension would tend to minimise the current overloading problem. This in turn would result in major improvements in the raw wastewater and secondary effluent quality, particularly in terms of parasite removal and lowering of TSS content.

ACE (1984) proposed a quality standard for TSE re-use for irrigation that takes into account the specific local conditions. These standard values were slightly modified by ACE (1989) as shown in Table 5.7. Table 5.8 summarises the analyses of the key parameters and heavy metals of the tertiary treated effluent from TWPCC for the year 2000. The average BOD and TSS values are 1.8 and 11 mg l^{-1}, respectively. These values indicate a BOD level within the proposed acceptable limit, with a TSS average concentration reaching the threshold level. The average turbidity value of 2.3 nephelometric turbidity unit (NTU) is just above the maximum recommended value of 2.0 NTU. The average ammonia-nitrogen concentration of 1.3 mg l^{-1} is well below the maximum recommended limit.

The occurrence of heavy metals in the tertiary effluent in toxic concentrations is remote (ACE, 1984). This is because of the fact that most of the wastewater coming to Tubli is of domestic and municipal origin. Comparing the heavy metals concentrations in Table 5.8 with those recommended in Table 5.7 further supports this assertion. The comparison clearly indicates that the average heavy metals values are well below the maximum allowable limits.

Table 5.7 Proposed local quality guidelines for wastewater re-use in agriculture (after ACE, 1984; 1989)

Parameter	Recommended limit/ maximum concentration	Parameter	Recommended limit/ maximum concentration
pH (pH unit)	7 - 9	Chloride (Cl^-)	1500
TDS	3500	Sulphate (SO_4^{2-})	700
Turbidity (NTU)	2.0	Boron (B^{3+})	1.0
BOD	10.0	Iron (Fe)	5.0
COD	50	Copper (Cu)	0.2
Total suspended solids	10.0	Zinc (Zn)	2.0
NH_3-N	5.0	Lead (Pb)	5.0
Nitrite (NO_2)	0.5	Nickel (Ni)	0.2
Nitrate (NO_3)	5.0	Cadmium (Cd)	0.05
Sodium (Na^+)	700	Chromium (Cr)	1.0
Potassium (K^+)	---	Mercury (Hg)	---
Calcium (Ca^{2+})	---	Residual Chlorine	1.0 – 1.5
Magnisium (Mg^{2+})	---	Total Coliform	2.2/100ml
Phosphorous (P)	10.0	Faecal Coliform	2.5/100ml
Boron (B)	2.0		

Notes: All values are in mg l^{-1}, unless otherwise stated.
A dash indicates no recommended limit set.

Table 5.8 Analysis of the key parameters and heavy metals of the tertiary treated effluent from Tubli WPCC January – December 2000

Month	TSS	VSS	COD	BOD	NH_3-N	Cu	Zn	Pb	Ni	Cd	Cr
January	10	3	29	1.4	0.54	0.02	0.95	0.08	0.02	0.01	0.30
February	8	3	28	1.6	0.71	0.02	0.31	0.06	0.07	0.01	0.40
March	10	4	40	1.9	1.00	0.10	0.55	0.09	0.08	0.01	0.40
April	11	4	21	2.3	1.58	0.05	0.53	0.10	0.00	0.01	0.30
May	8	3	27	1.9	0.60	0.05	0.47	0.07	0.00	0.02	0.20
June	9	4	25	1.9	0.64	---	---	---	---	---	---
July	10	3	22	1.5	1.35	---	---	---	---	---	---
August	20	5	32	2.6	5.50	---	---	---	---	---	---
September	14	5	24	1.9	0.43	---	---	---	---	---	---
October	11	4	28	1.8	1.69	0.13	---	0.02	0.50	0.0	0.00
November	8	2	26	1.8	0.76	0.22	0.05	0.00	0.40	0.00	0.00
December	10	3	32	1.6	0.40	0.05	0.15	0.00	0.50	0.00	0.00

SOURCE: Tabulated from data obtained from Tubli WPCC.
A dash Indicates parameters not analysed. All values are in mg l^{-1}.

Table 5.9 presents monthly chemical analysis of the inorganic constituents of the tertiary treated effluent from Tubli WPCC for the year 2000. In general, the TDS concentration of the TSE is less than those of groundwater available for irrigation, except for limited areas in the northwestern and northern coasts where the Dammam aquifers contain somewhat lower salinity (refer to the discussion of groundwater salinity trends in Chapter Four). Currently (2000), the average total dissolved solids of the TSE is 3,685 mg l^{-1} with domination of chloride and sodium ions, confirming the domestic origin of the treated wastewater. The salinity of the Tubli tertiary effluent is slightly inferior to the maximum limit set in the proposed local standard, and is well above the international guideline limits. Of course, with this salinity level, only the salt tolerant crops can survive, but farming experience in Bahrain shows that some other crops can be successfully grown when proper on-field management is adopted.

The TDS concentration was initially projected by ACE (1984) to improve from 4,400 mg l^{-1} in 1985 to about 2,200 mg l^{-1} by the year 2000. However, the recent salinity data show that the salinity of the tertiary effluent has improved at a slower rate than previously anticipated. This is because the secondary sewers and desalination water projects are not progressing as planned. Also, infiltration from shallow groundwater has greatly contributed to the recent salinity increase. With the recent and planned expansion in desalination capacity and renovation of the secondary sewers, however, the wastewater salinity is expected to improve gradually.

From the agricultural point of view, boron, chloride, and sodium are toxic ions when present in high concentrations. The boron average concentration of 0.57 mg l^{-1} is quite acceptable and well in line with the recommended criteria, but chloride and sodium

Table 5.9 Monthly averages of the inorganic constituents in the tertiary treated effluent from Tubli WPCC January – December 2000

Month	Temp. °C	pH	TDS	Alkal.	Hardn.	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}	PO_4	NO_3^{-}	NO_2^{-}	B
January	24	7.3	4308	160	980	185	123	756	48	510	1847	3.1	2.75	0.020	0.53
February	24	7.4	4348	152	1210	182	141	967	55	594	2000	3.4	2.32	0.034	0.71
March	25	7.1	4063	178	1268	198	125	811	47	572	2010	3.5	2.52	0.074	0.72
April	28	7.3	4156	141	1193	158	101	656	42	576	1845	3.5	1.97	0.024	0.75
May	29	7.1	3608	137	1247	129	87	675	41	469	1553	4.6	1.00	0.012	0.69
June	30	7.1	3527	137	818	---	---	---	---	405	1713	4.4	0.90	0.018	0.27
July	32	7.2	3336	143	1077	---	---	---	---	375	1607	3.9	1.09	0.052	0.75
August	33	7.4	3464	138	1095	---	---	---	---	455	1550	3.2	1.33	0.088	0.41
September	31	7.2	3523	150	1028	184	159	---	---	363	1535	2.4	1.03	0.078	0.62
October	30	7.1	3249	129	903	177	99	810	44	406	1430	2.8	1.14	0.272	0.53
November	27	7.1	3136	137	1060	143	88	683	36	353	1680	2.5	2.38	0.136	0.38
December	26	7.2	3504	147	995	161	93	717	41	455	1770	2.7	1.79	0.016	0.43

SOURCE: Tabulated from data made available by Tubli WPCC.

Notes: All values are in mg l^{-1}, except pH in pH unit, and temperature as indicated. Alkal is alkalinity, and Hardn is hardness.
A dash Indicates parameters not analysed.

average concentrations of 1,714 and 759 mg l^{-1} are above the maximum recommended values. Again, such high sodium and chloride concentrations are quite normal for Bahrain groundwater, which is still the main source of wastewater. Phosphorous shows values within the allowable limits. In fact, phosphorous in the tertiary treated effluent is found at concentration that would enhance soil fertility and, hence crop production. The average concentration of this parameter in the Tubli effluents is 3.1 mg l^{-1}, against a recommended maximum concentration of 10 mg l^{-1}. Nitrite and nitrate contents are also within the allowable limits. Potassium content, although relatively high, studies show (WHO, 1989) that it does not have any adverse effects on soil or crops. No recommended value is set for this parameter in the proposed local standard. This is also the case with regard to the calcium and magnesium.

The recommended microbiological quality guidelines for treated wastewater use in agriculture (WHO, 1989) are shown in Table 5.10. The major quality parameters in these guidelines are faecal coliforms and parasites. The guideline values for unrestricted irrigation are ≤1000 numbers/100ml (geometric mean) faecal coliforms, and ≤1 (arithmetic mean) parasites egg per litre. Analysis of samples obtained from the ozone contact tank is presented in Table 5.11. The table gives geometric mean of 3.0/100ml faecal coliforms, and an arithmetic mean of 18 number per litre parasite larvae. The faecal coliform content is well below even the more stringent limits, but is slightly higher than the proposed local standard (2.5/100ml).

The reported parasites concentration is high and represents a major challenge to the water resources planners who consider the treated effluent as a strategic and cost-effective source of water to supplement groundwater supply. Of greater concern, previous analysis

Table 5.10 Recommended microbiological quality guidelines for wastewater use in agriculture [1] (after WHO, 1989)

Category	Reuse conditions	Exposed group	Intestinal neomatodes[2] (arithmetic mean no. of eggs per litre)[3]	Faecal coliforms (geometric mean no. per 100ml)[3]	Wastewater treatment expected to achieve the required microbiological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[4].	Workers consumers, public	<1	<1000[4]	A series of stabilisation ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[5].	Workers	<1	No standard recommended	Retention in stabilization ponds fro 8 -10 days or equivalent helminth and faecal coliform removal
C	Localised irrigation of crops in category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

Notes:

1. In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account, and the guidelines modified accordingly.
2. Ascaris and trichuris species and hookworms.
3. During the irrigation period.
4. A more stringent guideline (<200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.
5. In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

indicates more parasites in the service reservoirs than in the tertiary plant, suggesting that these microorganisms are reproducing in the transmission lines (Gur, 1991). However, this parasite level is controlled and reduced in the post-chlorination process in order to meet the WHO guidelines of ≤1 parasite egg per litre. Normally, the reported concentration after the post-chlorination is between 2 - 3 parasite larvae. Plant officials believe that this problem can be entirely eliminated once the problem of overloading has been overcome, and the proposed modifications to the secondary treatment processes have been completely implemented. Owing to the absence of local virological analytical facilities, viruses are not regularly analysed. However samples sent abroad at different times indicate almost virus-free treated effluent.

Table 5.11 Pathogenic micro-organisms in the tertiary effluent from Tubli WPCC January - December 2000

Months	Faecal coliforms (numbers/100 ml)	Parasites (numbers/litre)
January	2.4	4
February	0.6	6
March	0.2	44
April	1.6	45
May	4.8	10
June	4.8	7
July	12.4	8
August	40	78
September	5.8	7
October	3.8	5
November	2.2	3
December	0	1
Mean	6.5*	18

SOURCE: Modified from Tubli WPCC
*3.0 numbers/100ml (geometric mean).

In light of the above information, one could argue that, apart from the TSS and parasite problem, which has been mainly caused by the temporary overloading, TSE from Tubli WPCC is of high quality, and is in line with the local and international requirements. With a rational re-use programme and proper management and monitoring, treated wastewater re-use should be considered as an important element in the strategy for the overall water resources development and management.

5.2.3 Health and Environmental Considerations

Although, pathogenic contamination was considered very remote, it was recommended that unrestricted irrigation with Tubli effluent should not be practised (Gur, 1991; Pescod, 1996). This is because there is always a potential health risk associated with the re-use of treated wastewater for irrigation, and from applying sewage sludge to the soil. Discharge of treated or partially treated effluent into the surrounding environment may also result in pollution problems. Therefore, to ensure a successful re-use programme and to minimise the possible adverse effects to the environment, certain precautionary measures should be adopted. The primary aim of these measures is to reduce the potential health hazards to plant workers, farmers, crop consumers, and public parks and sport fields users, and to protect the environment from pollution (ACE, 1984; Gur, 1991; PES, 1995; Pescod, 1996).

According to the revised WHO guidelines, the helmenthic quality of treated effluents has become the most important quality parameter (Gur, 1991). As mentioned earlier, the parasites in the treated wastewater from Tubli are appearing in high concentrations, which represents a real threat to the human health both from direct use and upon contact. Thus, from the water resources planning standpoint, the need for effective removal of these pathogens to ensure high quality effluent is essential if an unrestricted or even a partially restricted re-use programme is to be considered.

Because of the soil characteristics in Bahrain and the municipal origin of the Tubli wastewater, accumulation of heavy metals and nutrients in soils and plant uptake in toxic levels is extremely unlikely (ACE, 1989). However, care should always be taken regularly to observe these compounds to prevent pollution to both land and marine environments. Heavy metals and pathogens are found in appreciable amounts in Tubli sewage sludge; therefore systematic monitoring and checking before application for these parameters are essential to eliminate health risks associated with its use.

The Ministry of Works and Agriculture is applying strict regulations for TSE and sewage sludge utilisation, although sanctions for non-compliance have not been prescribed. For example, before being allowed to receive TSE, farmers have to sign an agreement, which prohibits the use of this water to irrigate salad crops (Pescod, 1996). Other requirements, although not adequately followed, such as wearing protective clothing in areas irrigated with TSE are also imposed. Farmers are informed on the possible health risks associated with irrigation by TSE, and are also advised on the choice of crops and irrigation methods. Using the treated effluent for swimming, car washing or construction purposes is completely prohibited. The agreement also requires farmers to wash crops irrigated with TSE with clean water before marketing. Sludge handling and use restrictions recommended by the WHO are reasonably observed. In addition, the Tubli WPCC operators and technicians are following proper safety procedures with regard to plant operations and sewage sludge handling. The CMC field personnel who may come in contact with the TSE are also encouraged to take basic health measures precautions.

From the environmental protection point of view, the environmental impacts of treated effluent utilisation warrant particular attention. The Environmental Affairs at the former Ministry of Housing, Municipalities and Environment has established quality criteria for disposing of secondary treated effluent into the sea, as well as regulations on the preferred disposal methods. Unfortunately, however, the Ministry of Health is playing a minimal role in the TSE utilisation programme. The necessary involvement of this ministry should include, among other things, setting of local standards for TSE re-use for both restricted and non-restricted irrigation, and providing of health education programmes for farmers and plant workers. Such programmes should concentrate on improving on-farm practices, and continuously monitoring of the health of farmers in particular (Pescod, 1996).

If the surplus quantities of TSE are to be used for groundwater recharge, then pilot hydrogeological studies should be conducted to investigate the viability and potential for this option, including regular monitoring of the TSE quality, particularly with respect to heavy metals, faecal coliforms and parasites levels. GDC (1986) and Al-Ghamdi (1999) have conducted preliminary mathematical modelling studies to assess the potential of recharging the Khobar and Rus - Umm Er Radhuma aquifers using both tertiary and secondary effluents. Both studies have concluded that recharging the aquifer systems with TSE is feasible and would be beneficial in terms of raising the piezometric heads and minimising losses from the Khobar to the Rus - Umm Er Radhuma.

5.2.4 Treatment Costs

When compared with the desalinated water, the treated wastewater from Tubli treatment works provides a cost-effective alternative to supplement the groundwater supply, which is already exhausted. If treated sewage effluent is not used for agriculture and landscape irrigation and the same level of agricultural activity is continued or increased, then the deterioration of the groundwater would continue and the other alternatives would be either to abandon agriculture or to invest in a more expensive water supply (PES, 1995).

The unit cost of production, transmission and distribution of the TSE at Tubli WPCC was estimated by ACE (1990) at BD 0.060/m^3 (US$ 0.16/m^3). This estimate was based on the production of an average of 12,300 m^3 day^{-1} of tertiary effluent. For an average production level of 26,000 m^3 day^{-1}, the unit cost of tertiary treatment, including operation and maintenance costs is estimated by PES (1995) at BD 0.052/m^3 or US$ 0.14/m^3. The unit transmission and distribution cost is estimated at BD 0.012/m^3, implying that the cost per cubic metre of production, transmission and distribution of 26,000 m^3 day^{-1} of tertiary effluent is approximately BD 0.064 (US$ 0.17/m^3).

At the current production rate of about 40,000 m^3 day^{-1}, the estimated unit cost at Tubli works, excluding transmission and distribution costs, is about BD 0.042/m^3, equivalent to US$ 0.11/m^3. The cost breakdown for this production level is presented in Table 5.12.

Table 5.12 Breakdown of estimated unit cost production at Tubli WPCC

Item	Estimated cost (BD/m^3)
Labour	0.015
Services	0.011
Consumables	0.002
Assets	0.001
Maintenance	0.001
Projects	0.012
Total unit cost	0.042

SOURCE: PES (1995).

For phase II expansion of the treated sewage effluent scheme, PES (1995) have developed cost estimates, which include the costs of transmission, storage and distribution facilities that are required to meet the irrigation requirements after 1997, but before the year 2010. The resulting total unit costs for the projected quantities as of 1997 and 2010 are presented in Table 5.13.

Table 5.13 Estimated unit costs of treated sewage effluent from Tubli WPCC for the years 1997 and 2010

Year	Quantity (Mm^3/year)	Prod. cost (BD/m^3)	Trans. & storage cost (BD/m^3)	Distrib. cost (BD/m^3)
1997	54.1	0.020	0.021	0.005
2010	70.0	0.019	0.020	0.006
Unit cost 1997		0.046		
Unit cost 2010		0.045		

SOURCE: Tabulated after data from PES (1995).

Studies (PES, 1995; ACE - Al-Moayed, 1997) have shown that the unit cost of production at Tubli WPCC is relatively higher than treatment costs in some other parts of the world; this is mainly attributed to the costs associated with the operation of the ozone plant. However, the economic benefit that can be achieved, in terms of groundwater conserved, is estimated at BD 4.0 million per year in 1997 and BD 5.2 million per year by the year 2010; plus the added benefit of reducing the mass pollutants discharged to the sea (PES, 1995).

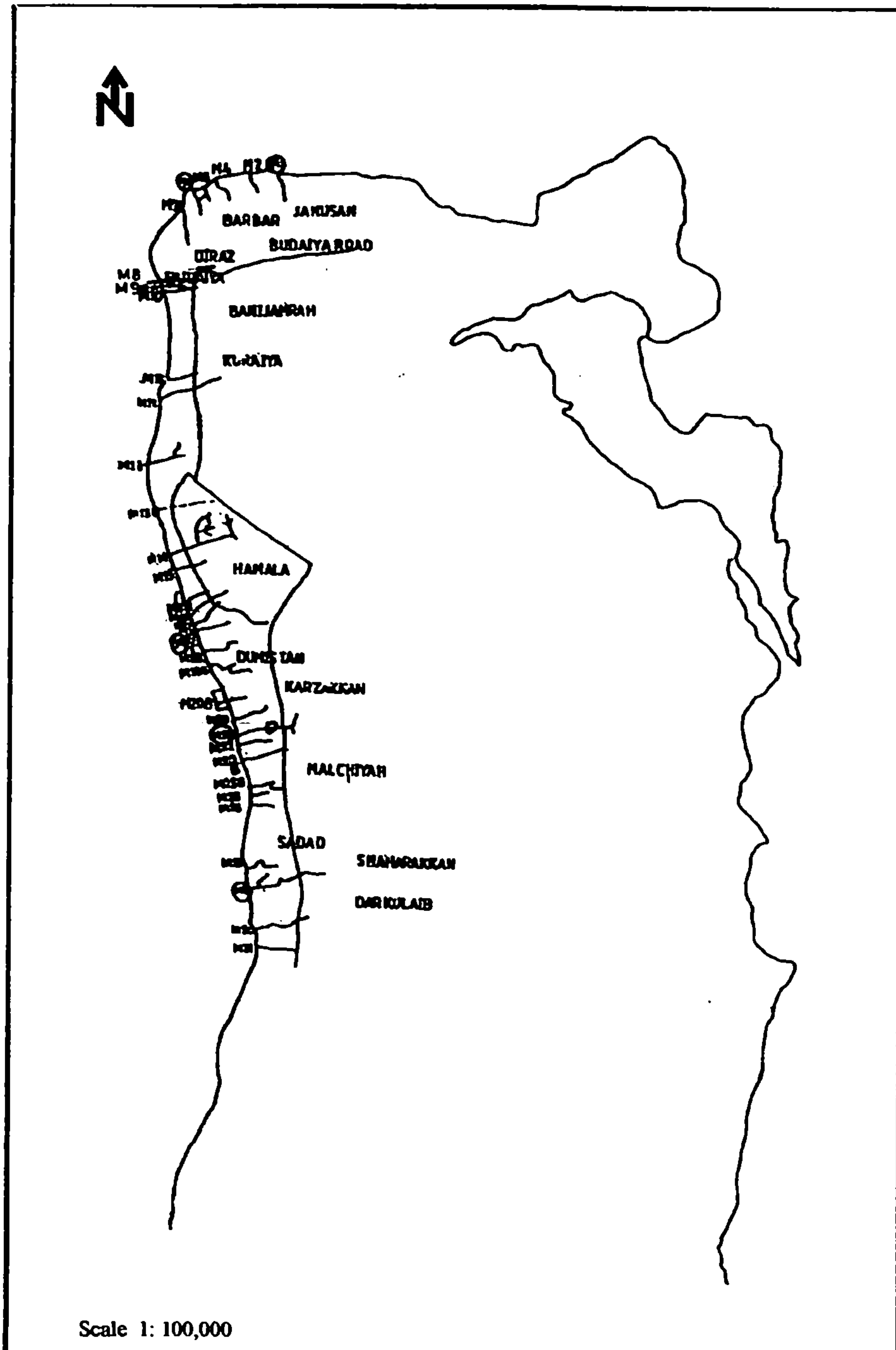
5.3 Agricultural Drainage Water

Most of the soils in the study area are coarse textured sandy to loamy sand, with high permeability and low water holding capacity, and are underlain at shallow depths, ranging between 0.3 – 2 m, by compact, relatively impervious, and commonly gypsum cemented calcium carbonate layer of the Neogene or Eocene deposits. This layer precludes free drainage within the soil profile and often causes water logging, soil salinisation, and hence reduction in crop production.

Consequently, installation of drainage systems to dispose of excess water and to control soil salinity has become an essential part in Bahrain's farming practice. Currently, there has been an extensive drainage system, with a total length of about 401 km, of which 146 km are main drains, 122 km lateral drains, and 133 km of field drains (Raj Kumar Singh, Drainage Department, written communication). Most of these drains are located in the northern, northwestern and western coasts consistent with the distribution of the agricultural lands. The locations of these drains are shown in Figure 5.3.

The aim of this section is to assess the potential of re-using the agricultural drainage water, which otherwise flows wastefully into the sea, for irrigation or other purposes. There are some 50 open ditches main drains constructed with sea outfall designs. Table 5.14 gives the approximate discharge from these drains and their salinities for the year 1990, along with their salinities for the year 2000. The table shows that the quantity of drainage water discharged from the main drains in 1990, based on measured discharge, amounts at about 76,939 m^3 day^{-1} (28.1 Mm^3 $year^{-1}$). Estimates for non-measured drains in some inaccessible private farms raises this total to between 30.3 – 30.9 Mm^3 (Al-Noaimi, 1993). Recent estimates on drainage discharge are not available. However, according to the Drainage Department officials (Raj Kumar Singh, Drainage Department, personal communication), a total amount of about 60,274 m^3 day^{-1} (22 Mm^3 $year^{-1}$) was expected to be discharged during the year 2000. Considering that groundwater used for irrigation

Figure 5.3 The locations of the main drains in the study area



SOURCE: Drainage Department of Ministry of Works and Agriculture

Table 5.14 Approximate discharge from the main drains as of 1990 and their salinities for the years 1990 and 2000

Drain no.	Location	Discharge (m^3 day^{-1})	Salinity 1990 (TDS-mg l^{-1})	Salinity 2000 (TDS-mg l^{-1})
M52	Sanabis	1728	15040	---
M1	Janusan	1900.8	4483	---
M2	Barbar	432	3597	9920
M4	Barbar	3024	3979	---
M5	Barbar	3196.8	4855	5056
M6	Barbar	1296	3944	3840
M7	Duraz	1728	5706	6144
M8	Budaiya	604.8	4261	---
M9	Quraiah	864	4885	4288
M10	Quraiah	691.2	5539	8000
M11	Janabiyah	1555.2	5515	6813
M12	Janabiyah	1382.4	4249	---
M13	Jasra	2160	4401	5559
M13(A)	Jasra	1209.6	3109	---
M13(B)	Jasra	1296	5648	---
M14	Jasra	1382.4	5665	6272
M15	Hamala	1987.2	7509	4493
M16	Hamala	1296	6650	4928
M16(B)	Hamala	1382.2	7748	---
M17	Hamala	1036.8	7457	9892
M18	Hamala	1209.6	7682	9619
M19	Karzakan	1900.8	7392	14278
M20	Karzakan	1296	9360	5220
M20(A)	Karzakan	1728	10322	---
M21	Karzakan	1468.8	11264	16448
M22	Karzakan	1036.8	11889	9837

Table 5.14 (Continued)

Drain no.	Location	Discharge (m^3 day^{-1})	Salinity 1990 (TDS-mg l^{-1})	Salinity 2000 (TDS-mg l^{-1})
M24	Malkiyah	691.2	10350	---
M25	Malkiyah	518.4	12098	---
M26	Sadad	2160	8331	12698
M27	Shahrakan	1814.4	7573	11252
M28	Shahrakan	1296	8290	11085
M29	Shahrakan	1814.4	11337	10480
M30	Shahrakan	7862.4	9350	10607
M31	Zallaq	3067.2	8487	11123
M32	Zallaq	1296	8500	7488
M33	Wasmiyah	864	10800	8461
ZQZ	Wasmiyah	1296	11500	---
ZQ3	Wasmiyah	1036.8	10600	---
ZQ4	Wasmiyah	1382.4	12000	---
MAR	Adhari	2592	10880	---
MTC	Tubli	1296	23040	---
MT1	Tubli	1036.8	15680	---
MT2	Kuwarah	691.2	5680	---
JB1	Jurdab	518.4	9280	---
JB2	Jurdab	1036.8	11840	---
UM1	Umm Nakhila	1296	13663	17600
UM2	Umm Nakhila	1555.2	11254	---
GLL	Qalali	2160	19950	17280
B11	Bin Hindi	864	12500	---
Total discharge		76939		
Average salinity			8880	9225

SOURCE: Tabulated from data made available by the Drainage Department – Ministry of Municipalities and Agriculture.
A dash indicates no data.

has gradually increased over the intervening period, such a reduction in drainage flow is probably associated with the lowering of water levels in the underground aquifers, since this factor has a major control on the quantity drained and discharged to the sea. Therefore, the official drainage discharge estimate of 22 Mm^3 $year^{-1}$, plus an allowance of 10 % (2.2 Mm^3 $year^{-1}$) for the non-accessible drains, or a total amount of about 24.2 Mm^3 may be assumed a reasonable estimate for year 2000.

The salinity of the drainage water is generally more than twice that of groundwater used for irrigation, because salts normally contained in irrigation waters are washed out in the soil profile, and are recovered in the drainage water. In 1990, the salinity of this water ranged between 3,109 and 19,950 mg l^{-1} TDS, with an average value of 8,880 mg l^{-1} (Table 5.14). The more recent data for year 2000 showed that this salinity has not increased appreciably, ranging between 3,840 and 17,600 mg l^{-1} TDS, with an average value of about 9,225 mg l^{-1}, or a 4 % increase over the 1990 salinity level.

Naturally, the salinity distribution of the agricultural drainage water directly reflects the salinity of the irrigation water, in which drainage water discharged in areas of relatively good quality groundwater has a lower dissolved solids concentration. However, deviation from this trend is evident in some drains. For instance, drains UM1 and GLL in Umm Nakhila and Qalali, respectively, show salinities as high as 17,000 mg l^{-1}. Water drained from M17 and M18 in Hamala also reveal high salinity values inconsistent with the general salinity pattern in this area. It seems probable that the former anomaly results from contamination by saline water from the Neogene aquifer (it is believed that this aquifer is opened to the sea in those areas). The Hamala anomaly is possibly caused by lack of efficiency of the drainage system or because most of the drainage waters that come to these drains are from individual saline wells.

Reuse of the agricultural drainage water for irrigation was first considered by ERCON (1973) who suggested that this water could be conveyed through a system of pumps and pipelines to a main collector sump for treatment, desalination, or mixing with fresher groundwater in areas where there is no groundwater or groundwater salinities are high, and from these to distribution networks. In areas where the drainage water contains lower dissolved solids, it can be used directly for fodder crops, date palms, and salt-tolerant vegetables in farms adjacent to the main drains. They also estimated mixing ratios to maintain a minimum quality of 4,000 mg l^{-1} TDS, with due adjustments for crop water and leaching requirements. Similar alternatives were proposed in the-mid 1980s in response to the marked deterioration in groundwater quality (MOCA, 1983). However, so far there has not been a clear government policy on drainage water reuse.

The major factors that determine the possibility and extent of drainage water reuse are its quality and the economic feasibility when water transportation and treatment are involved. Table 5.15 distributes the available drainage water based on their discharge and salinity levels for the years 1990 and 2000. The discharge rates for 2000 were computed based on the 1990 measured discharges, assuming a fixed decline of 20 % in each drain. It should be noted that the crucial point here is that the drains in a particular salinity level in the year 2000 were not exactly the same as those in 1990 as indicated by the change in the percentage distribution for each category in Column 5. This is because of the salinity deterioration during the comparison period. The table reveals that the majority of the drains (53.1 % in 1990 and 61 % in 2000) contain water of salinity of more than 8,000 mg l^{-1}, with discharges of 15.67 Mm^3 and 8.6 Mm^3 in 1990 and 2000, respectively.

Table 5.15 Classification of agricultural drainage water based on its salinity and discharge levels

Salinity levels (mg l^{-1})	Discharge (Mm^3)		Percentage distribution (%)	
	1990	2000	1990	2000
Less than 5,000	5.90	1.6	20.40	11.33
5,000 – 8,000	6.65	3.9	26.53	27.67
More than 8,000	15.67	8.6	53.07	61.00
Total discharge	28.1	14.1	100%	100%

Those of salinities between 5,000 to 8,000 mg l^{-1} discharged about 6.65 Mm^3 in 1990, and 3.9 Mm^3 in 2000, representing about 26.53 and 27.67 %, respectively. The quantity of drainage water of salinity less than 5,000 mg l^{-1} was estimated at about 5.9 Mm^3 in 1990, decreased to 1.6 Mm^3 in the year 2000, equivalent to a considerable decrease of 73 %.

This table provides a reasonable basis for possible drainage water re-use management, and could be frequently refined once more accurate and updated information becomes available. For example, the quantity of drainage water with salinity lower than 5,000 mg l^{-1} TDS, although very small, could be successfully used in its present state or by mixing with some fresher groundwater for date palms or fodder crops and salt tolerant vegetables. On the contrary, the use of drainage waters with salinities higher than 8,000 mg l^{-1} may be considered not feasible. Drainage water containing TDS in the range of 5,000 – 8,000 mg l^{-1} may be used indirectly in agricultural areas having no groundwater or more saline groundwater. This water could also be used for landscape irrigation for some salt-tolerant trees.

The amount of drainage water presently reused for irrigation is limited to 0.24 Mm^3 per annum, and is used in two farms located in Janabiyah and Janusan villages occupying an area of about 7 ha. These farms rely upon drainage water of salinity between 3,900 – 5,000 mg l^{-1} to irrigate fodder crops, date palms and some salt-tolerant vegetables. The preliminary results of these experiences were very encouraging and need to be regularly evaluated for possible extension to other farms.

It is expected that with the wide reuse of TSE as part of Phase II expansion, about 50 km of additional main drains will be required (ACE - Al-Moayed, 1997). With the expected improvement in the TSE salinity as a result of expansion in desalination capacity, the quality of drainage water is likely to improve markedly. This would increase the total drainage discharge and the amount of this water within the first category (less than 5,000 mg l^{-1}). Therefore, with this situation ahead, a long-term policy on drainage water reuse not only for agriculture and landscape irrigation but also for possible groundwater recharge should be seriously considered at high level.