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SUSTAINABLE GROUNDWATER DEVELOPMENT OF HARD-ROCK AQUIFERS : THE CONFLICT BETWEEN IRRIGATION AND DRINKING WATER SUPPLIES FROM THE DECCAN BASALTS OF INDIA

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Natural Environment Research Council

International Division
British Geological Survey
Keyworth
Nottingham
United Kingdom NG12 5GG

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D M J Macdonald[1], H C Kulkarni[2], A R Lawrence[1], S B Deolankar[2], J A Barker[1] and A B Lalwani[2]

[1] Hydrogeology Group, British Geological Survey, Maclean Building, Wallingford, Oxfordshire, OX10 8BB, United Kingdom
[2] Department of Geology, University of Pune, Pune 411 007, Maharashtra State, India

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Large-diameter dug well, Pabal Village, Maharashtra, India

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Executive Summary

In many developing countries groundwater is the primary source of drinking water for the rural population. This is particularly true in the semi-arid regions, where it may be the only source of perennial freshwater. Groundwater occurs in a wide range of rock types and usually requires little or no treatment, therefore it is often the cheapest and simplest water supply option.

However, the rising demand for water worldwide, mostly for irrigation, can lead to problems of overexploitation of these resources and to conflicts with competing demands, especially with community potable supplies. These problems are accentuated in those areas underlain by hard rocks[1], since the aquifers present usually store only limited quantities of water in shallow weathered and fractured layers. Further, in the semi-arid regions, the climatic conditions of low and variable rainfall limit recharge and make these aquifers susceptible to drought.

This report is based on a three-year study, funded by the Overseas Development Administration's (ODA) Technology Development and Research (TDR) programme as part of the British Government provision of technical assistance to developing countries, which aimed to assess the sustainability of yield of wells and boreholes in hard-rock aquifers. The study area selected was in the state of Maharashtra in west India.

In India, there has been a tradition, going back many centuries, of using groundwater both for irrigation and for potable supplies. Historically, abstraction from the shallow aquifer has been limited, mainly because water-lifting devices were animal-powered. However, since the 1950s groundwater abstraction has increased substantially, both as a consequence of the increase in the number of wells, and of progressive replacement of the animal-powered lifting devices by motorised pumps capable of much higher yields. In the state of Maharashtra, groundwater abstraction has risen more than seven-fold since the 1950s. Concern has been expressed in India as to whether this considerable increase in groundwater abstraction is largely responsible for the decline of groundwater levels and the 'drying-up' of both irrigation and community water supply wells. The problem of relating cause to effect is complicated in this instance by the 'natural' groundwater fluctuation resulting from the variability of the monsoon rains.

The most important aquifers in the state of Maharashtra are the Deccan basalts. The research study investigated the groundwater system in one village, typical of many in the area. It attempted to evaluate the long-term impact of groundwater irrigation on water-levels and the likely effect on potable supplies, which are entirely from village community wells. Whilst the results of this research relate to the study area they are believed to have wider application and interest.

This study has shown that groundwater abstraction for irrigation is currently the largest component of discharge from the aquifer, and that the water-table at the end of the dry season declines, as a result of this pumping, to near to the base of the aquifer.

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[1] Hard rocks: a term used to describe volcanic or ancient crystalline rocks; porosity and permeability are normally low and restricted to the weathered and fractured layers.

Therefore, a further increase in groundwater abstraction is not possible as all the available water in the aquifer has been utilised.

Monitoring over a 12-year period, has provided clear evidence of a long-term water-level decline, as a result of increased groundwater abstraction. This decline in water-level has resulted in one positive consequence: the long-term average annual recharge has increased. This is because groundwater levels no longer approach the ground surface at the end of the monsoon and therefore rainfall infiltration is not rejected due to lack of available storage within the aquifer.

However, negative consequences include a decline in dry season river flow (outside of the monsoon period river water is entirely derived from groundwater) and the widespread drying-up of wells following a 'failure' of the monsoon. Deepening of wells does not appear to be a viable option as most wells already fully penetrate the shallow weathered aquifer.

Since more than 70% of India's population live in rural areas and, given the importance of groundwater to the rural economy, it is clear that efficient management of groundwater resources is essential. Effective groundwater management requires, firstly, a good understanding of the aquifer system, secondly, that practical measures to control abstraction can be identified and, thirdly, that any legislation is both equitable and acceptable to the rural community.

The State Government of Maharashtra has recently introduced legislation to safeguard community drinking water supplies based on a protection zone policy. Such intervention is very much welcomed, although there is a need to review and monitor the effectiveness of the implementation of this legislation and, where necessary, to make recommendations for its improvement.

This report strongly recommends that deeper aquifers are not developed for irrigation but are reserved for emergency drinking water supply only.

1. Introduction

In the semi-arid regions of the world, water for potable supplies and for supplementary irrigation is obtained mostly from shallow groundwater. Many of these areas are underlain by 'hard rocks': volcanic or ancient crystalline rocks, where groundwater most frequently occurs in aquifers within the shallow weathered and fractured layers. Yields from individual wells are usually low, less than 50 m^3/d, and the quantity of water stored in these aquifers is often relatively small, perhaps equivalent to only 2-3 years average annual recharge, or even less. Further, the climatic conditions, low and variable rainfall, limit the quantity of recharge available to these aquifers and makes them susceptible to drought. The significance of these limitations are crucial as the aquifers often represent the only available source of water.

In many developing countries where population growth is high, demand for water often outstrips supply and shortages occur both locally and regionally. Water shortage areas are likely to expand in coming years due to increasing demand and competition for a finite resource. Worldwide, agriculture now accounts for about 80% of all water use and the total area under irrigation tripled between 1951 and 1980 (Bastemeyer and Lee, 1992). Domestic consumption, which generally accounts for less than 10% of the water withdrawn, is especially at risk when in competition with other water uses.

In India, there has been a tradition, going back many centuries, of using large diameter dugwells for both potable supplies and for irrigation. In the hard-rock areas of peninsular India, these wells are still the principal source of water. Groundwater is more popular with farmers than canal water since they have more choice over when it is used, how much is used, and what type of crops they may irrigate with it (Sawant *et al.*, 1991).

Food production in India has managed to keep pace with population growth, despite the rapid increase in recent years from approximately 350 million in 1950 to more than 800 million in 1990. This significant achievement has been attributed to various factors including: higher applications of chemical fertiliser and pesticides; improved seed varieties; and, perhaps most importantly, an increase in the irrigated area.

In the hard-rock areas of India, the increase in irrigated area has been a consequence of many more wells and an increased rate of abstraction per well. The increase in the number of dugwells in recent years is indeed substantial. For example, in the State of Maharashtra alone, the number of dugwells has increased from approximately 1 million in 1984 to more than 1.5 million in 1994; most of these wells are used, at least in part, for irrigation. Until recently, water lifting devices relied upon manual or animal power, which effectively limited the quantity of water that could be withdrawn. However, since the 1950s these water lifting devices have been progressively replaced by motorised pumps capable of much higher abstraction rates.

The considerable increase in the quantity of groundwater pumped from these shallow aquifers (Hebbalkar, 1984) has raised, in many peoples' minds, doubts as to whether such a level of irrigation development in the hard-rock aquifers is sustainable[2]. These concerns have been heightened in recent years by widespread reports of falling groundwater levels and the drying-up of shallow wells. For example, in Maharashtra excessive groundwater exploitation for sugar cane cultivation has been blamed for causing village wells to dry up, whilst in Gujarat state, the introduction of mechanised irrigation pumps is thought responsible for lowering the water-table, leaving nearly 300,000 people without water (Bastemeyer and Lee, 1992). However, though overexploitation of groundwater resources may be responsible for excessive drawdowns, it is important not to underplay natural fluctuations in the water-table, for example the recession of the water-table in drought years (Dhawan, 1995). Therefore, knowing the causal factors of the fluctuation in the water-table must be a pre-requisite to effective groundwater management.

It is important to recognise that irrigation wells and drinking water wells are in competition for the same resource; depletion of water resources, due, to excessive abstraction by irrigation wells, may result in public drinking water wells drying-up. In Maharashtra, the state government, aware of the need to protect public drinking water wells, has proposed legislation designed both to restrict the sinking of new wells within a critical zone (500 m radius) around a community drinking water well (i.e. a protection zone) and to regulate abstraction from existing irrigation wells during times of water scarcity. Whilst such a positive initiative must be welcomed, the criteria used to define the protection zone needs to be based on scientific evidence. In addition, the implementation of the policy may encounter serious practical difficulties. Nevertheless, the concept of protecting drinking water wells is a good one and needs encouragement and support.

In response to these concerns a study was undertaken jointly by the Geology Department of the University of Pune and the British Geological Survey, as part of the project 'Sustainability of groundwater supply from hardrock aquifers' (Project R5551), funded by the Overseas Development Administration (ODA) under its Technology Development and Research (TDR) programme. The TDR programme forms part of the British Government's provision of technical assistance to developing countries. A similar case study, to be reported separately, was carried out in Zimbabwe.

The objectives of the study in India were to:

(i) evaluate the groundwater system in an area representative of the Deccan basalt environment of central-west India, and investigate the changes to the system that have occurred as a result of the significant increase in groundwater abstraction for irrigation,

(ii) assess the impact of increased irrigation water demand on groundwater levels, and in particular on water-levels in public drinking water wells,

(iii) assess whether the present level of groundwater development is sustainable, and

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[2] The sustainable level of groundwater development is defined here as the quantity of water that can be pumped, expressed as long term average, for an indefinite period without serious detrimental impact on other users.

(iv) suggest measures which might be introduced to protect drinking water sources.

Guide to the report:

A review of the geology and hydrogeology of the Deccan Basalts and a history of the development of groundwater resources in this region is given are Chapter 2.

The case study is introduced in Chapter 3. This includes a description of the objectives, the geography and the socio-economic setting of the area and the project programme.

The water-level and abstraction data collected in the case study area are presented in Chapter 4. These data are used to obtain a water balance for the aquifer. The analysis and the results of pumping-tests carried out as part of the project programme are also described. These results are used to model near-well water-levels in the aquifer to allow the influence of the pumping of irrigation wells on the regional water-table to be estimated.

In Chapter 5, further modelling is used to allow the results obtained from the case study to be generalised. The implications of this modelling are included in a discussion of the options for protecting communal groundwater sources of drinking water. One particular option for source protection, recently introduced to Maharashtra State, is evaluated.

The results of the project are broadened into a discussion of sustainable groundwater development in Chapter 6 and of the implications for groundwater policy. Future needs to improve the understanding of the status of groundwater resources are suggested.

The conclusions from the project and the recommendations for further work are presented in Chapters 7 and 8.

2. Geology and hydrogeology

2.1 Deccan basalts

The Deccan Basalts (also referred to as the Deccan Traps) occupy an area of more than 500,000 km² in west-central India (Figure 2.1) and average 600 m in thickness. The lavas which formed the Deccan Basalts erupted in the Cretaceous/Tertiary period, some 65 (±10) million years ago. In general the Deccan Basalt flows can be placed in two categories, 'simple' or 'compound', depending on the viscosity of the primary lava. The simple flows equate to classic flood basalts formed by quiet effusive eruption of very large quantities of low viscosity lava from open fissures. The compound flows are either the product of more explosive activity from a more viscous lava or can be formed at the distal portion of simple flows where there is an increased viscosity from cooling and de-gassing. Geographically, compound flows dominate in areas around Pune, Bombay and Nasik, while simple flows dominate in the plateau regions to the east, south and north-east of the Deccan Basalts (Deshmukh, 1988).

The Deccan Basalts are formed from many individual lava flows, varying from a few metres up to 100 m in thickness. A typified sequence within a single flow is described below and summarised in Figures 2.2a & 2.2b (see also Photographs 2.1a & 2.1b).

1)	amygdaloidal upper layer:	spheroidal amygdales and vesicles; progressively more rubbly upwards with a network of sub-horizontal sheet joints,
2)	compact lower layer:	generally without vesicles, amygdales or sheet joints; local vertical or columnar jointing in the upper part above a massive base with irregular and pipe vesicles and amydales.

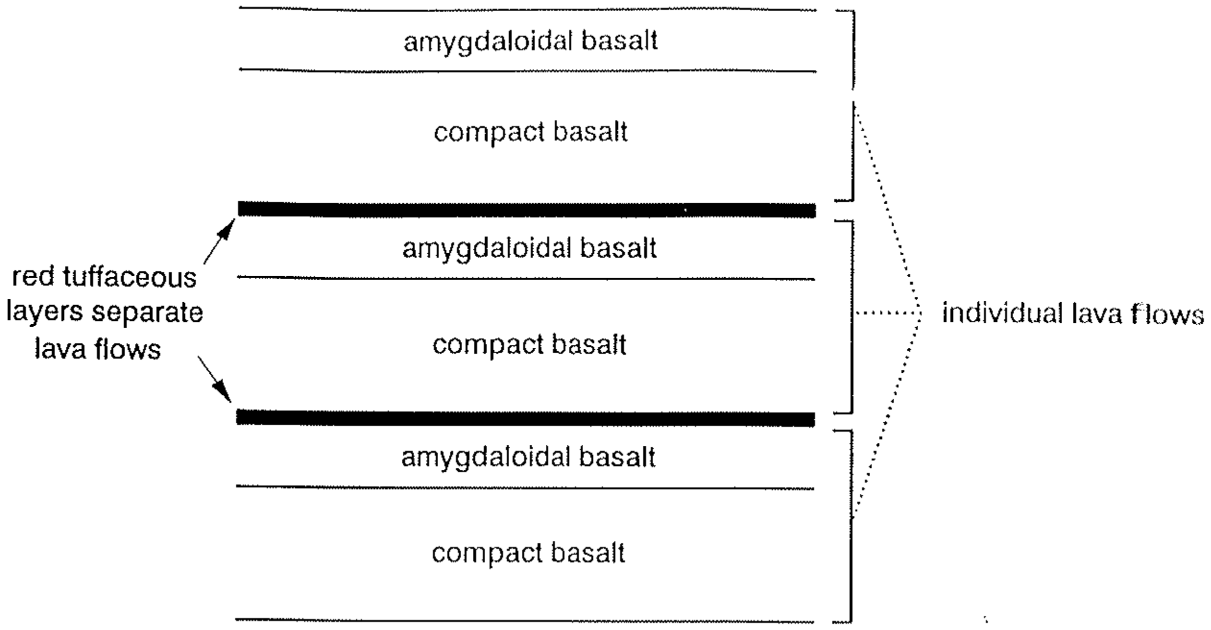
Individual flow units are normally separated by fine-grained material with a tuffaceous or scoriaceous appearance, reddish or greenish brown in colour. Such interflow horizons, also referred to as 'red bole', are quite friable, especially when exposed. These layers are clearly apparent in surface exposures and in well sections and form good marker horizons for geological mapping. In boreholes they give strong gamma peaks on geophysical logs and are invaluable for section correlation.

The relative thicknesses of the two layers within the flows vary with the flow type and hence has a major influence on the groundwater potential of the basalt.

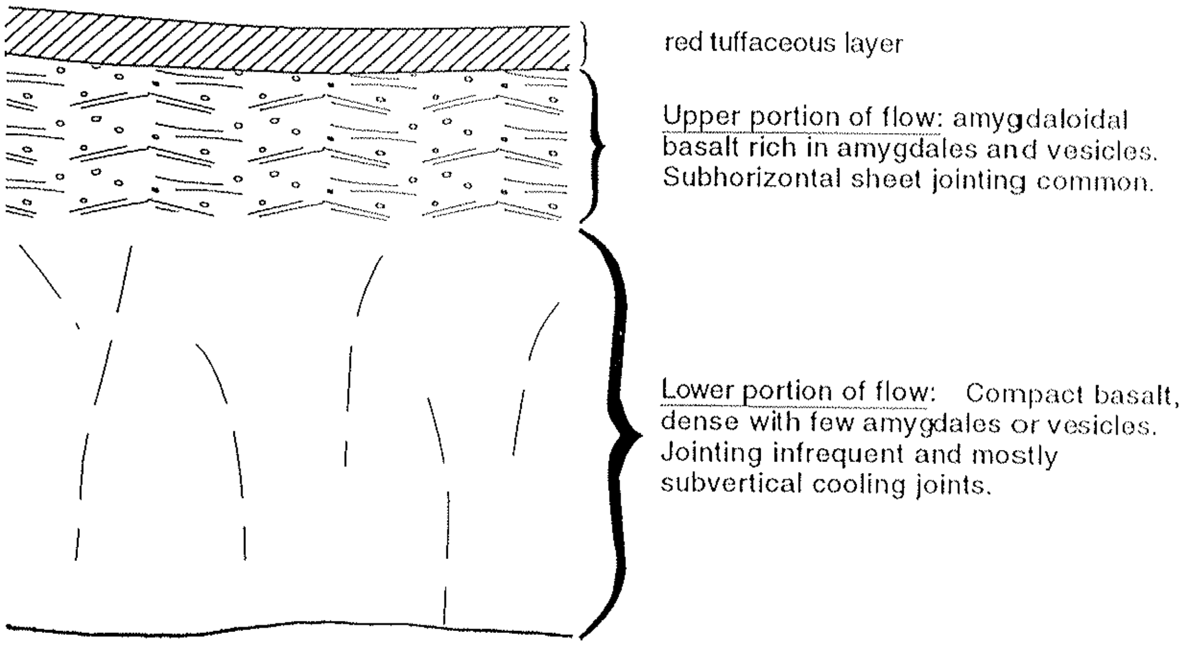
Simple flow basalts

These basalts are formed by lavas that spread over the ground surface with extensive fronts. Both the upper and lower portions of the lava chill rapidly and solidify, thereby trapping the volatiles degassing from the lava and imparting the vesicular nature. These layers are relatively thin compared with the compact central portion of the lava. The central portion cools very slowly and may remain fluid for years. The upper and lower margins of the flow become fractured, partly by shrinkage on cooling and partly due to distortion by the movement of the still liquid central portion of the flow.

Figure 2.1 Map of India showing the location of the study area and the extent of the Deccan Basalts



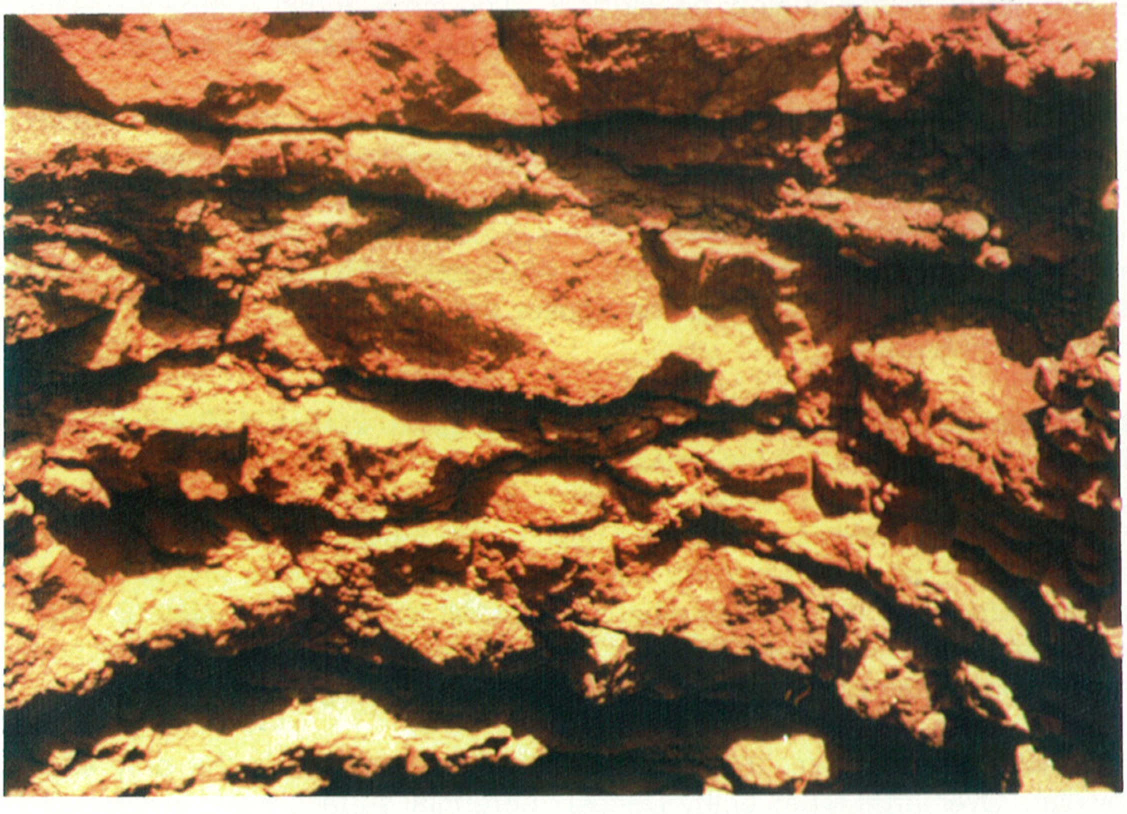
a) repetitive sequence of amygdaloidal and compact basalts



b) single lava flow

Figure 2.2 Simplified section through Deccan Basalt lavas

Photograph 2.1a Example of the compact lower layer of a lava sequence showing sub-vertical jointing



Photograph 2.1b Example of the amygdaliodal upper layer of a lava sequence showing sheet jointing

Compound flow basalts
These basalts result from lavas which lose much of their volatile gases prior to extrusion and hence are more viscous. This greater viscosity causes what volatile gases remain to be trapped within the rapidly solidifying lava. The lava is characterised by rubbly upper and lower surfaces. Fragmentation of the upper surface results from the disruption of the viscous crust by the movement of the flow beneath it. Some compound flows may be devoid of a compact middle layer.

Although distinction is made between the two flow types, gradations between simple and compound flows are not uncommon since the effects of the loss of volatiles and cooling will increase the viscosity of the lava and cause a change in physical characteristics.

2.2 Groundwater System

Groundwater occurs within the shallow weathered and fractured zones of basalts. Shallow aquifers exist over most of the area covered by the Deccan basaltic lavas; only where unweathered basalt occurs at the surface, is the existence of shallow groundwater in doubt. The shallow aquifer is normally considered to be unconfined, extending to depths of 15-20 m only. The upper portion of the shallow aquifer is generally more weathered and friable; the degree of weathering decreases with depth and the basalt becomes progressively more competent. The thickness and degree of weathering of layers within the shallow aquifer is very variable and dependent upon the type and nature of the original basalt flow. The more dense compact basalts are generally less weathered and usually form the base of the shallow aquifer.

The amygdaloidal basalts associated with compound flows weather more readily and frequently possess closely spaced subhorizontal sheet jointing. In some areas of the Deccan plateau, especially within the state of Madhya Pradesh, the basaltic lavas are covered by an appreciable thickness (3-10 m) of 'black cotton soils' and clay, probably of colluvial origin (Hodnett and Bell, 1981). Although these clays are not widespread, where present they partly confine the aquifer and significantly reduce the effective infiltration.

Aquifer transmissivities are usually low, in the range 20-200 m^2/d (Deolankar, 1980). Higher transmissivities reflect the presence of well developed sheet joints. The specific yield, or storativity, of the shallow aquifer is also variable, laterally and with depth. However, few direct measurements have been made. Specific yield values of between 2 and 12% have been obtained for weathered basalt (Lawrence and Ansari, 1980), although values are much lower where the basalt is overlain by clay (0.1%). The specific yield of less weathered lavas is likely to be less than 5%. The low-moderate storativity means the aquifer has a very limited water storage capacity.

The basaltic aquifer is important because in many areas it is the only source of freshwater. Over large areas of the Deccan, perennial surface water is restricted to a few of the larger rivers. Small streams flow during and immediately after the monsoon only. Gullies on the basalt hills testify to the rapid runoff that can occur, however, many of these water courses 'disappear' on reaching the relatively low slopes of the plains.

The shallow weathered aquifer has been exploited for many centuries for domestic water supply and for minor irrigation by shallow large diameter wells. These wells which are typically 4-10 m in diameter are ideally suited for exploiting low permeability aquifers since they provide considerable well storage. During the day when water is withdrawn, well storage is depleted; inflow overnight from the aquifer allows water-levels in the wells to recover. Well productivity can be variable; average abstraction rates are in the range 100-200 m^3/d, although some wells can supply over 500 m^3/d, suggesting the presence of well developed sheet joints in the basalt lavas. Lower well yields are associated with the more compact and denser basalt lavas (Deolankar, 1980).

Deeper confined aquifers are known to exist within the basaltic lava sequence, however they are considered to be generally of limited extent (Versey and Singh, 1982). Recharge to these deeper aquifers is also generally limited, occurring mostly as leakage from the shallow aquifer via sub-vertical fractured zones. In areas where productive aquifers occur at depth, recharge is believed to take place by vertical fracture zones (Kulkarni and Deolankar, 1993) which extend to the ground surface, intercepting surface water flow during the monsoon. Such occurrences are not common.

2.3 History of groundwater development

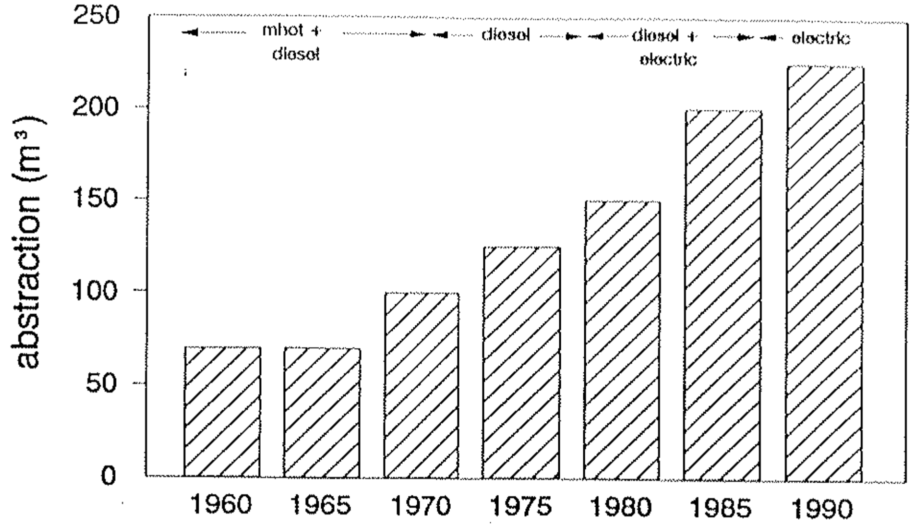
In India, groundwater constitutes a very important source of water supply, particularly in the rural areas. During more recent times, groundwater has also gained importance in larger cities where it is used as a supplementary water source for domestic supplies. Some industries have moved away from the city making fresh demands on the groundwater resource.

Irrigation by groundwater has been practised for many centuries in India. Until the 1950s almost all abstraction from these shallow dugwells was either done manually or by animal powered 'mhots' (Photograph 2.2). This limited the quantity of water that could be withdrawn from individual wells. The 1950s saw the introduction of mechanical water lifting devices which progressively replaced the mhots over the next few decades.

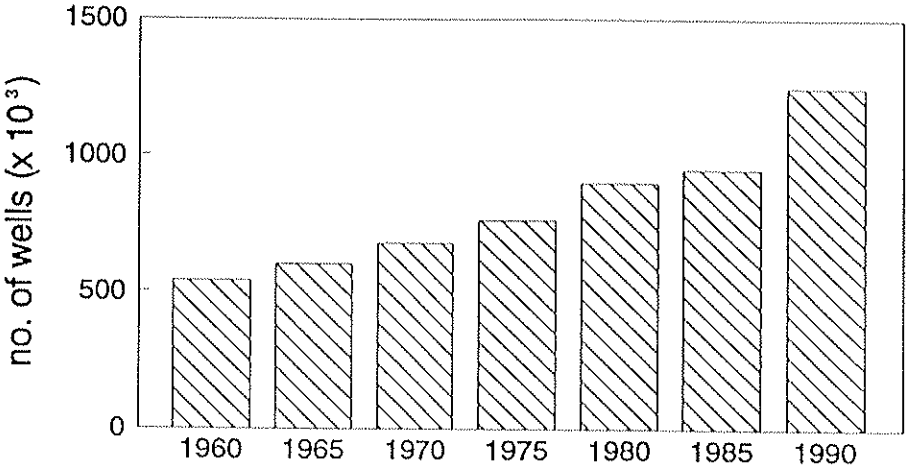
Diesel powered pumps initially took over from mhots. There was some limitation to the amount of water pumped from the dugwells using these devices due to the cost of fuel. Electrically powered pumps have taken over from diesel pumps over the last few years as electricity supplies reach even the most remote villages. The electric pumps used in shallow dugwells are generally of high capacity and can run over longer periods. The result of the change in pumping methods has been a dramatic increase in the average abstraction per well since the 1950s (Figure 2.3a).

Photograph 2.2 Water being lifted from a shallow dug well using a leather pouch (mhot), pulled-up using animal power

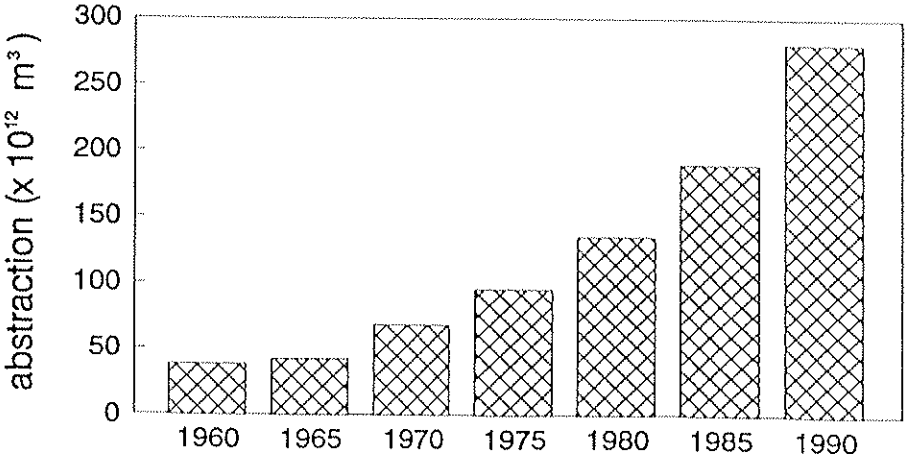
Photograph 3.1 Pabal study area with bounding low-lying hills in background



a) average daily abstraction per irrigation well and principal method of abstraction



b) number of irrigation wells



c) average total daily abstraction from all irrigation wells

Figure 2.3 Well number and groundwater abstraction data for Maharashtra State

In addition to the increase in abstraction there has also been a considerable increase in the number of shallow irrigation wells (Figure 2.3b). This is due, in part, to encouragement by the Government to develop groundwater resources for small scale irrigation. In the state of Maharashtra, there are more than 1.5 million shallow wells at present. This number is increasing by 30,000 to 40,000 each year. The combination of the increase in pumping capacity and the number of wells has meant that the total daily abstraction in Maharashtra has increased by over 700% (Figure 2.3c) since the 1950s.

The depth of traditional large-diameter wells is limited by the thickness of the shallow weathered layer and the occurrence of compact basalts. As shallow groundwater resources are exhausted some richer farmers have resorted to the drilling of small-diameter boreholes, sometimes from the base of existing dugwells (dug-cum-borewells), to tap the deeper aquifers. Over 135,000 boreholes have been drilled in Maharashtra by the Groundwater Surveys and Development Agency (GSDA) alone (Phatak and Ingley, 1990). Deeper aquifers are not always of high enough transmissivity to be economically viable. However, in some places favourable conditions do exist and deeper aquifers constitute the only source of water (Lalwani, 1993). Where significant abstraction occurs, recharge to the deeper aquifer will be by induced leakage from the shallow aquifer above. Therefore, increased abstraction from the deeper aquifer may result in falling water-levels in the shallow aquifer. This will disadvantage the poorer population who rely on the shallow groundwater resources (Moench, 1992).

3. Research programme: Pabal case study

3.1 Objectives of the case study

To obtain a more detailed insight into the causes of falling water-levels, and their implications for water resources, an investigation was carried out in a rural area of Maharashtra State underlain by Deccan basalt. The area is located near Pabal village in the Shirur taluka of Pune district, north-east of Pune city (Figure 2.1). Investigations were initiated in this region in 1983 by the Department of Geology of the University of Pune (Kulkarni, 1987) and the study described here benefited very much from the information previously gathered.

The case study aims to evaluate the groundwater system in the area and the changes that have occurred to it as a result of the increase in groundwater abstraction. It will do so by answering the questions:

(i) what proportion of the water balance is groundwater abstraction for irrigation?

(ii) what effect does abstraction from irrigation wells have on the regional water-levels in the aquifer?

(iii) is there any evidence of a long-term trend in groundwater levels?

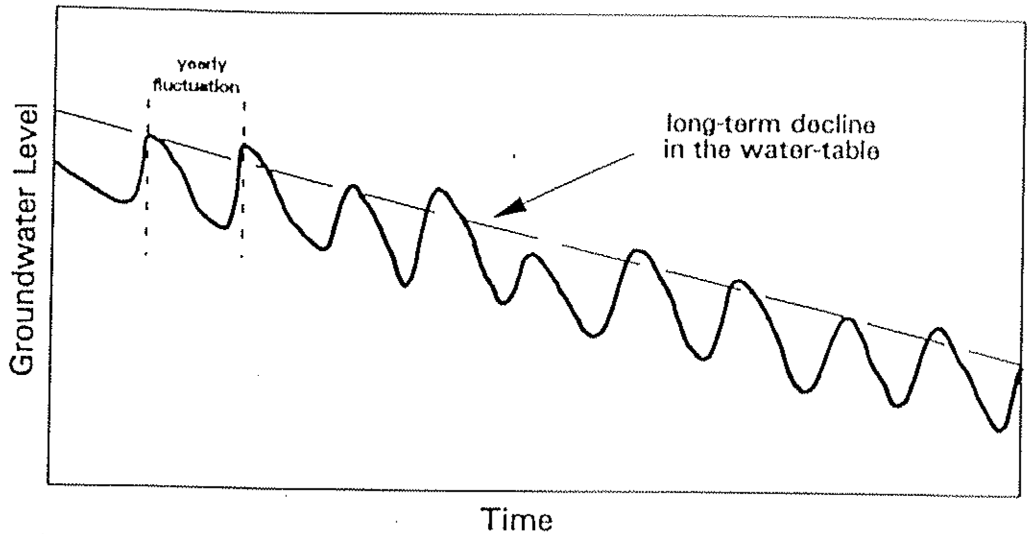
The cause(s) of water-level decline is central to the specific objectives of the case study. Groundwater levels can decline for a number of reasons (Fig 3.1):

(1) the total quantity of water discharged from the shallow aquifer exceeds the average annual recharge, producing a long term decline in the water-table (Figure 3.1a),

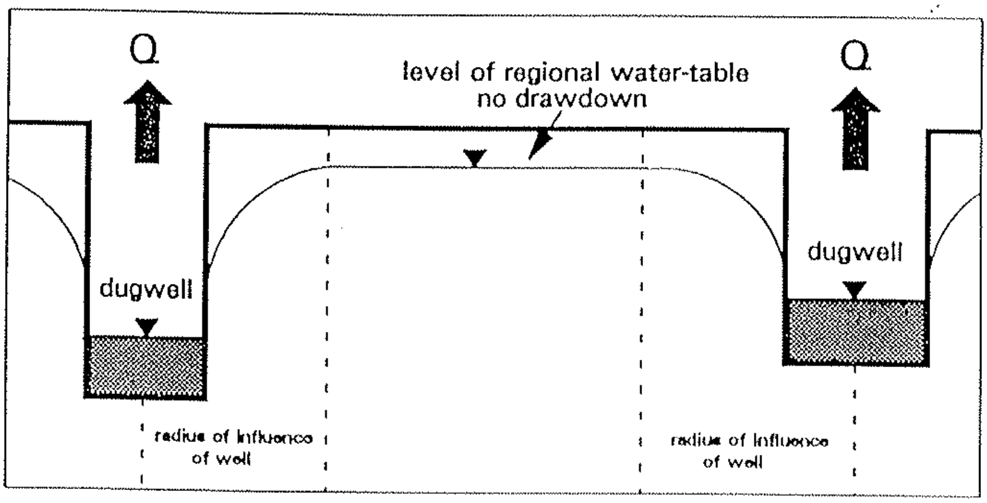
(2) the abstraction rate exceeds the capacity of the aquifer to transmit water to the well at a sufficient rate, thus depleting aquifer storage locally around the irrigation well (Figure 3.1b). This may result in individual abstraction wells 'drying up' although the total groundwater discharge from the aquifer does not exceed the average annual recharge. In this case the low permeability of the aquifer regulates abstraction,

(3) the total quantity of groundwater discharged from the aquifer does not exceed the average annual recharge but successive 'dry' years have resulted in lower than average recharge producing a short term decline in water-levels (Figure 3.1c). Water-levels may decline over successive dry years but recover once rainfall returns to normal.

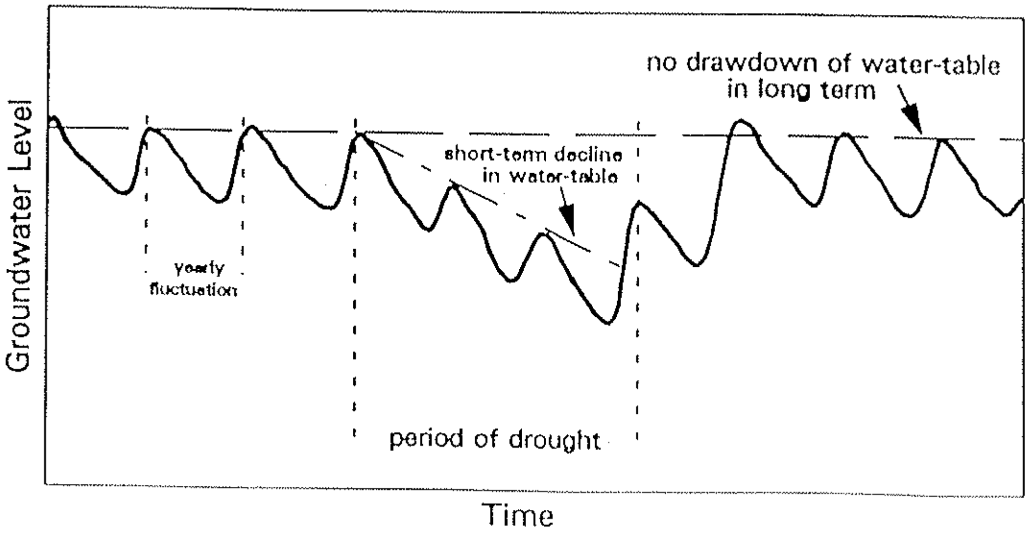
The case study aims to identify which of the above scenarios is predominant in the Pabal area.



a) long-term decline in water-level



b) seasonal localised water-level decline



c) short-term decline in water-level due to period of drought

Figure 3.1 Schematics illustrating causes of well water-level decline

3.2 The Study Area

Pabal village is a relatively highly populated centre with an area of 0.2 km^2. The village has several satellite inhabitations which are situated in the intensively cultivated trails around the village. The population of the village plus the surrounding settlements is approximately 8000. The study area is located 500 m to the north-east of the village and covers an area of 2.34 km^2 (Figure 3.2). This includes 1.5 km^2 of cultivated land which is generally quite flat. The outer boundaries are defined by gently sloping basaltic hills of low relief (Photograph 3.1).

The climate of the region is semi-arid: temperatures range between 20°C and 38°C during the summer months (March-June) and 10°C and 30°C in the winter (November-February). Rainfall tends to occur during one monsoon season (July-October). Figure 3.3 shows the yearly totals for the period 1900-1980 at a nearby rain station (20 km south-east). This would appear to suggest an approximate 18 year cycle to the rainfall with a standard deviation of 159 mm/annum about the mean of 532 mm. Rainfall data for Pabal itself has been collected over a period of 11 years (Figure 4.2). During the years 1993 and 1994 when the majority of the fieldwork for this study was undertaken the monsoon rains amounted to 559 mm, and 385 mm, respectively.

Figure 3.2 shows a cross-section of the geology of the area. The cultivated land is almost totally restricted to the area of outcrop of the amygdaloidal basalts. The bounding hills are formed by compact basalts. The soils on the hills are thin or absent and they are generally not cultivated. The thickness of the amygdaloidal basalt generally decreases towards the south-west and is almost absent in the area of Pabal village where compact basalts can be found at outcrop. The surface water drainage in the area is constituted by two non-perennial streams flowing south-west. These form part of the Vel river system. The amygdaloidal basalts are the main source of drinking and irrigation water for the area.

All the flat land in the study area is cultivated for at least 8 months of the year. A rainfed crop normally of groundnut or maize is planted in July and harvested in October. The following (winter) crop of onion, maize, wheat, jowar or potatoes is heavily irrigated by groundwater and is harvested in February or March. A third crop may be grown during the summer months, depending on water-levels in the wells. These, in turn, are dependent on the rainfall during the preceding wet season. In some years land may be left fallow to save groundwater resources for drinking water supply. If grown, the summer crops are mainly vegetables and fodder. Some wells also support small fruit orchards of mostly lemons and oranges.

Dugwells are the only type of well constructed in the study area. Two attempts to obtain groundwater using deep boreholes have both failed. The average diameter of the dugwells is 5.0 m and the average depth is 10.2 m. The deeper wells occur in the east of the area where the thickness of the amygdaloidal layer is greater. Historically, wells have been deepened in response to low recharge periods when water-levels drop below the well base. The period following the failed monsoon of 1986 saw six wells being deepened. However, at present, half the wells in the study area penetrate to the compact basalts and the potential for increased yield if these wells are deepened, is low.

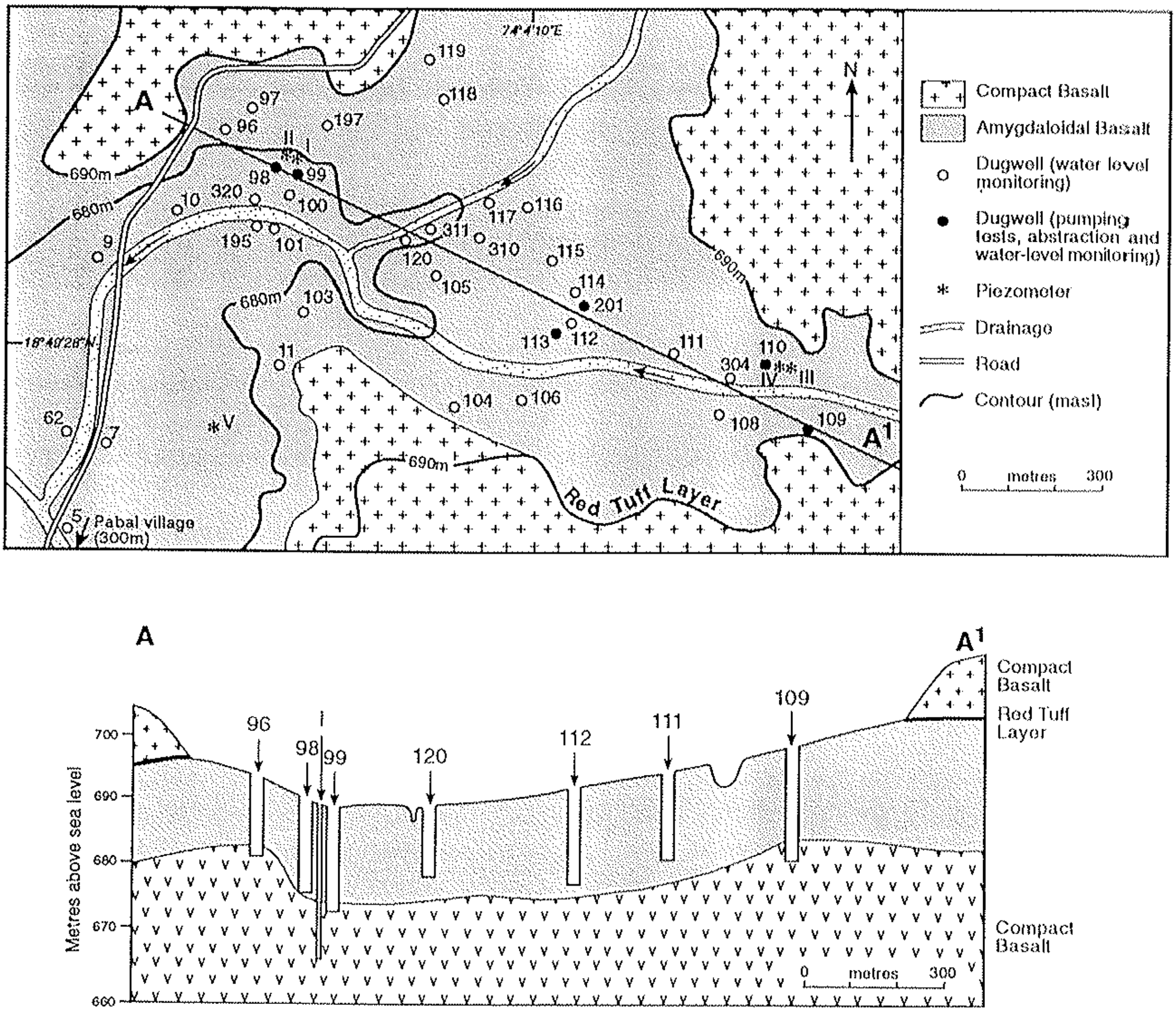


Figure 3.2 Basemap and geological cross-section from Pabal study area

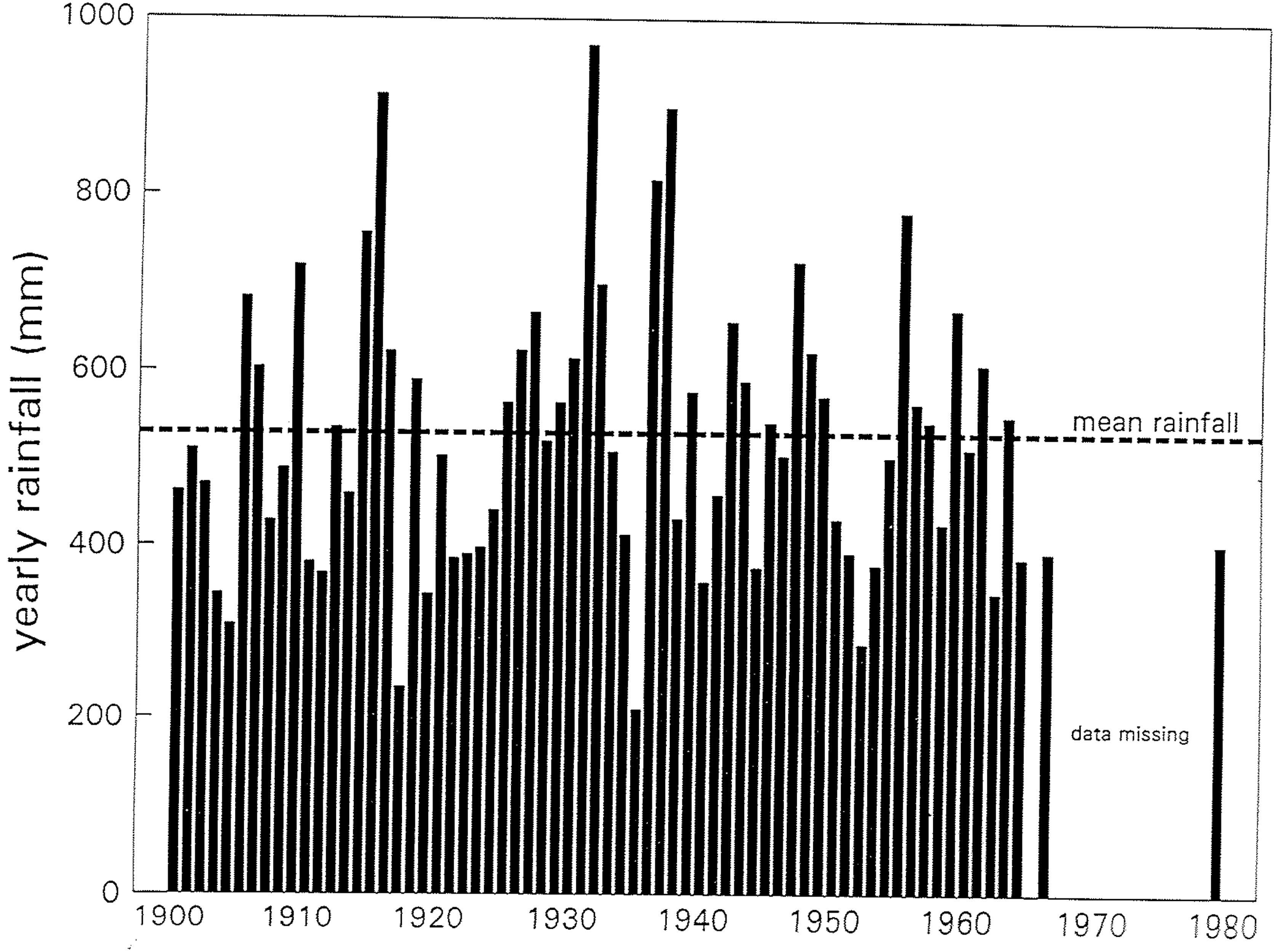


Figure 3.3 Yearly rainfall data, 1900-1980, from a raingauge station 20 km south-east of Pabal village

There are 39 wells within the study area. Eight of these have been constructed since 1987. The trend is to dig wells of larger diameter; the average diameter of the recently dug wells is more than 9 m. Each well may have more than one owner. As land is shared between generations so is the ownership of wells . In one case a well, the most productive in the area, has more than 20 owners. This can result in long periods of pumping and the installation of more than one pump per well. It has also been reported that some owners will pump without having the need for water, simply to assert their rights to a share of the well ownership.

3.3 Project programme

As previously mentioned, investigations have been carried out in the Pabal area since 1983 and are described in Kulkarni (1987). The work carried out as part of this study built upon data already collected. The programme included:

- monitoring of rainfall
- monitoring of water-levels in all dugwells in the study area
- monitoring of abstraction from five selected dugwells
- pumping-tests on the five selected wells
- drilling of two pairs of boreholes in the vicinity of three of the selected wells, to monitor near-well water-levels
- drilling of a borehole distant from dugwells to monitor the regional water-level
- pumping-tests carried out on dugwells with boreholes as observation holes.

In addition, a database was set-up to hold baseline information on the wells in the study area.

4. Results of the case study

4.1 Water-level monitoring

The water-levels in 36 of the dugwells in the study area have been monitored over the period of the project. Data are also available for the period November 1983 to November 1986. During this period water-levels were measured twice a year: in November, following the monsoon rains, when water-levels are at their maximum; and in May, at the end of the dry season, when water-levels are expected to be at their minimum. Apart from one well (well 99), monitoring did not restart until June 1993. From January 1994 monitoring was carried out on a monthly basis. In addition, water-levels have been monitored since October 1994, in 5 observation boreholes, drilled as part of the project.

A survey of wells and their pumping regimes showed that the abstraction from several of the dugwells is negligible. The water-levels in these wells have been used to indicate how the water-table fluctuates in the areas where the localised effects of pumping are minimal. These data, although limited, suggest that for 1994/95 the depth to maximum (post monsoon) water-level is on average 3.5 m and that the annual fluctuation is on average 3.5 m. A comparison of water-level fluctuations in non-pumping wells and pumping wells (Figure 4.1) shows that the water-table declines relatively uniformly throughout the aquifer.

There are many more water-level data going back to 1983, for those wells in the study area from which abstraction is significant (approx. 24). These data show an increase in the depth to the maximum water-level over the 12 year period to the present (Figure 4.2). Maximum water-levels in 1984 were typically within 1.5 m of the surface, compared with approximately 4 m in 1994. This is a significant drop as the average well depth is only 10 m. It appears that the current groundwater recharge is not sufficient to bring water-levels in the aquifer as close to the surface as previously. A similar decline in groundwater levels has been observed for the period 1977-1987 in the Deccan Basalts in other areas of Maharashtra (Agashe, 1989 and Mehta, 1990). Analysis of the minimum water-levels for 1985 and 1994 shows an increase in the proportion of wells running dry by the end of the dry season. In May 1985 one of 29 wells surveyed was dry. Of the same set of wells seven were dry at the end of the dry season in 1994. Even though the monsoons prior to the dry season of 1985 were greater than those preceding the dry season of 1994, Figure 4.2 suggests that the reason for the increase in the number of wells drying-up is the long-term decline in water-levels. The result of this decline is that a significant number of wells have had to be deepened over the last decade.

4.2 Abstraction monitoring

The vast majority of water abstracted within the study area is for irrigation. The pattern of abstraction has generally been dependent on the cropping (Kulkarni and Deolankar, 1993). Five wells were chosen for more detailed monitoring of abstraction. The monthly abstraction figures for the 1993/94 season are shown in Figure 4.3. The months of July to October have relatively low levels of abstraction as this is the period

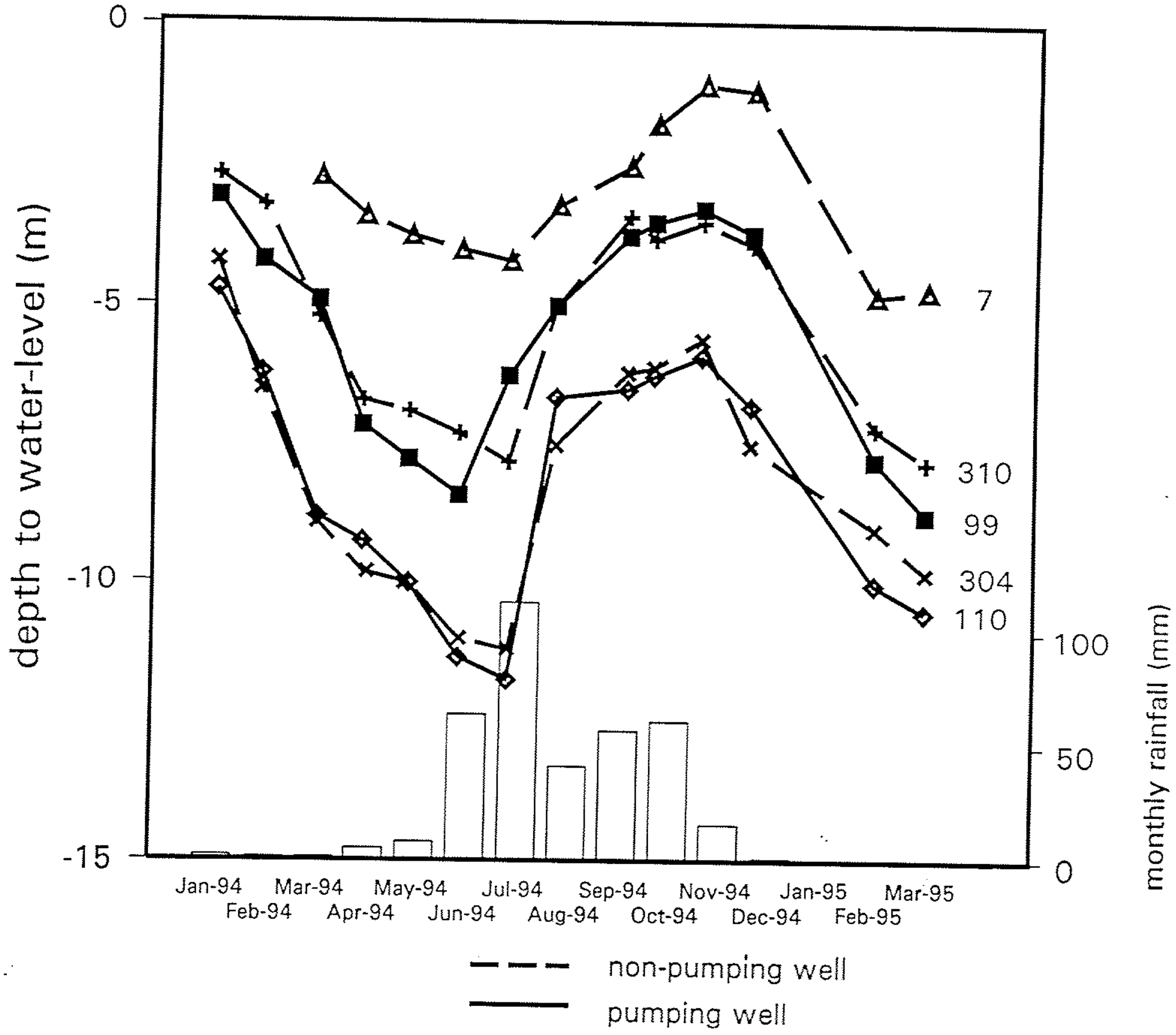


Figure 4.1 Well water-levels in pumped and non-pumped wells and monthly rainfall data from the Pabal study area, 1994/95

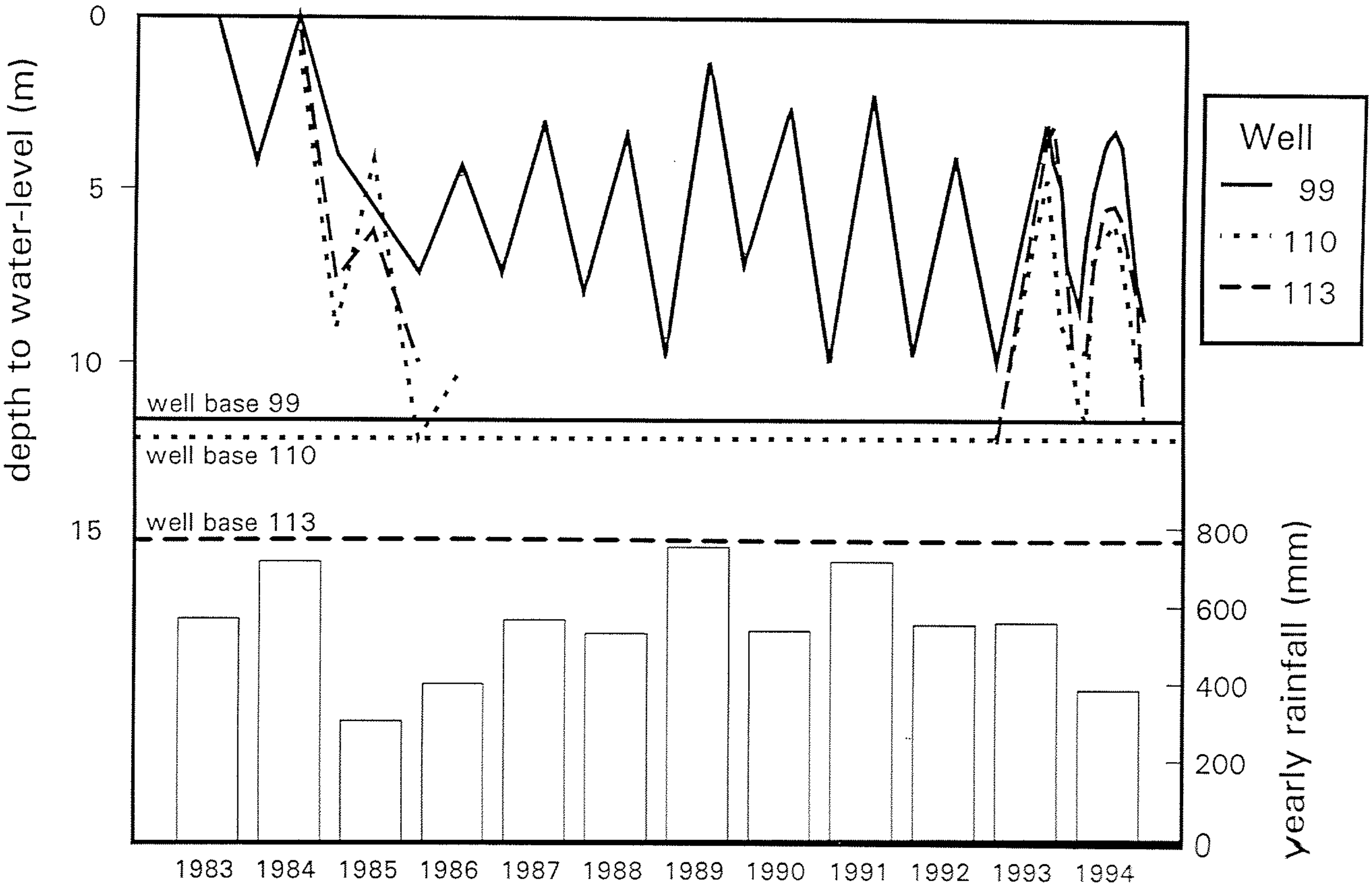


Figure 4.2 Well water-levels and yearly rainfall data from the Pabal study area, 1983-1994

of the monsoon and the crops are rainfed. Once this is harvested the winter crop is planted. This is totally dependent upon groundwater irrigation and large volumes are required, as can be seen by the substantial increase in abstraction in November (planting of the winter crop in the case of well 99 occurred later). The winter crop is harvested during February-March. A summer crop may be grown depending upon the availability of water. The area cultivated is always much smaller than for the winter crop and as a consequence irrigation is much reduced even in years when the monsoon rains are above average. When the monsoon rains are below average, wells may start to run dry or produce low yields during March. In these years the area cropped during summer may be negligible.

The pattern of abstraction of the five wells highlighted here is broadly typical of many in the area although their pumping rate is significantly higher than most. A survey of most wells in the study area indicated an average well yield of 85 m^3/d, with an estimated total volume pumped of 5×10^5 $m^3/year$.

4.3 Water balance

An understanding of the groundwater system requires a quantitative assessment of both the inputs to (recharge) and the outputs from (discharge) the aquifer. The components of the groundwater system are shown in Figure 4.4. During the period November to May there is little or no rainfall recharge and the discharges from the aquifer can be equated with the release of water from aquifer storage:

$$\Delta s = Q_p + Q_a + R_d + E_t + B_f \qquad (4.1)$$

where Δs = volume of water released from aquifer storage (specific yield x water-level fluctuation)
Q_p = groundwater pumped from wells
Q_a = aquifer throughflow
R_d = recharge to deeper aquifers
E_t = evapotranspiration directly from the water-table
B_f = baseflow contribution to streams

In Pabal, abstraction from the irrigation wells modifies the groundwater flow pattern and limits considerably the quantity of water that flows beyond the study area and consequently, Q_a is small (ie. the bulk of groundwater flow is directed to the wells themselves). The baseflow contribution to streams is also quite small. Recharge to deeper aquifers can be discounted since no deeper aquifers have been identified and therefore there is no pumping to induce recharge. Evapotranspiration losses are negligible since the water-table is normally more than 3 m below the surface.

The water balance can therefore be simplified to:

$$\Delta s = Q_p + Q_a + B_f \qquad (4.2)$$

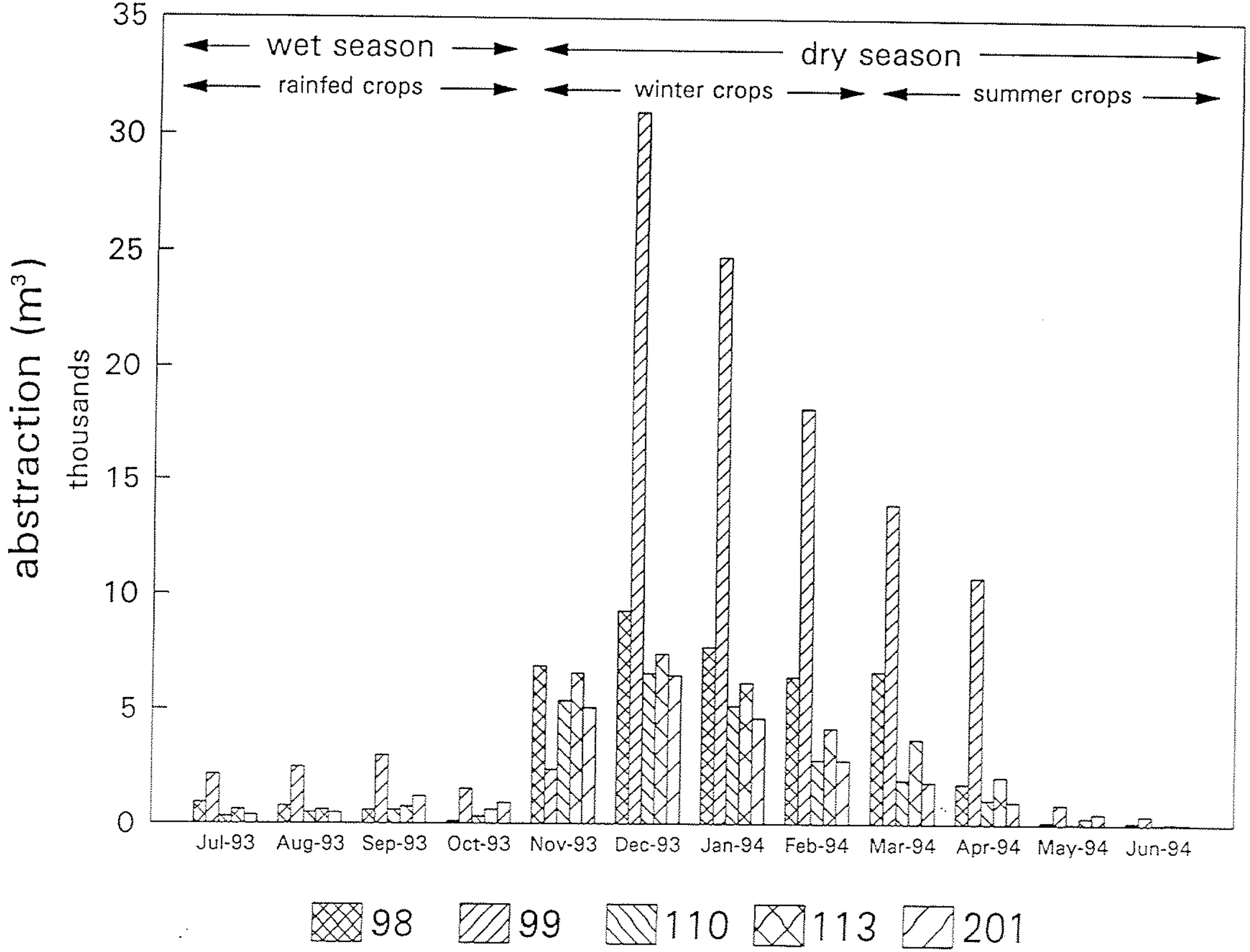


Figure 4.3 Monthly well abstraction totals for 5 wells in the Pabal study area, 1993/94

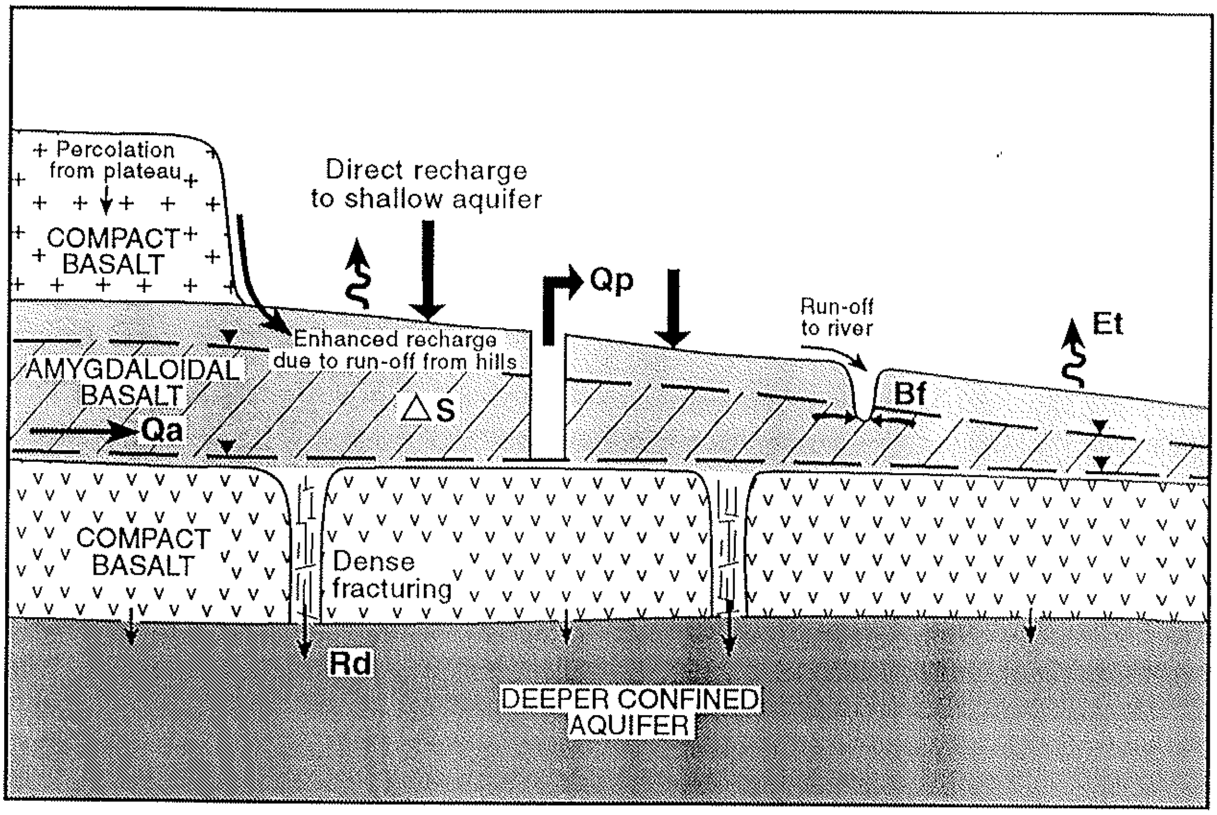


Figure 4.4 Conceptual model of the groundwater flow system in a basaltic aquifer

Q_p has been estimated at 5×10^5 m^3 per year which is equivalent to 240 mm over the cultivated area. However, some of the irrigation water will infiltrate below the soil layer and recharge the water-table. A figure of 30% has been used to calculate recharge from irrigation return flows in the Deccan basalts previously (Lawrence and Ansari, 1980). Thus the net abstraction is about 160 mm.

Allowing for some 10-15 mm to account for the minor components of discharge from the aquifer system (ie. Q_a and B_l), the total 'losses' from the aquifer amount to approximately 175 mm. The release from aquifer storage is equivalent to the product of the actual water-level fluctuation and the specific yield of the aquifer. Measured water-level fluctuations average about 3.5 m, so the specific yield can be estimated:

$$S_y = \frac{\Delta s}{\Delta wl} = \frac{175mm}{3500mm} = 0.05\ (5\%) \qquad (4.3)$$

This is not an unreasonable estimate of specific yield for a weathered and jointed bedrock and is in broad agreement with specific yield determinations in other areas of the Deccan (Deolankar, 1980 and Lawrence and Ansari, 1980).

The figure of 175 mm represents the volume of water released from the aquifer and since the water-level rise following recharge from the monsoon rains is of similar magnitude to the decline of the water-level during the dry season, this figure of 175 mm approximates to the average infiltration to the aquifer. However, some of the rainfall on the low hills of compact basalt contributes to the recharge of the aquifer. This recharge may occur either by direct infiltration through sub-vertical jointing, or more commonly, by runoff from the hills, which subsequently infiltrates through the soil on the lower lying cultivated land where the amygdaloidal basalt is exposed at surface. If the recharge is calculated over the whole of the catchment, the infiltration is closer to 120 mm. Even so, this figure is large when compared with the average annual rainfall of 550 mm and infers that a larger proportion (22%) of the rainfall can infiltrate to groundwater than was previously thought likely. In India, estimates of recharge in hard-rock terrains are normally considered to be in the range of 8-10% (Lerner *et al*, 1990).

4.4 Pumping-tests

A series of pumping-tests (or aquifer tests) were carried out to obtain values of aquifer transmissivity. These values were then used to model the water-levels in the vicinity of wells and in the aquifer as a whole.

There are many difficulties with both performing and analysing pumping-tests in these environments.

(1) It is impossible when performing a pumping-test on a well to avoid interference effects from other wells being pumped for irrigation. The drawdown and recovery of water-levels measured therefore do not necessarily reflect pumping from the test well alone. This may lead to errors when estimating aquifer

parameters from the test. In addition, there may be a residual drawdown in the well due to pumping from the well itself by the farmer some hours prior to the test.

(2) The analysis of pumping-tests on large-diameter wells is more difficult than for slim boreholes due to the large storage within the well itself and the uncertainty in estimating well dimensions.

(3) Weathered aquifers due to their heterogeneous nature do not meet the assumptions and conditions of a homogeneous isotropic aquifer of infinite extent that are normally assumed when analysing pumping-tests.

(4) During the pumping-tests, the water pumped is used by the farmer for irrigation. If this water recharges the aquifer by return flow it will cause errors in the aquifer parameter estimation, especially for late-time data.

Acknowledging these difficulties, a series of pumping-tests were carried out on five wells (the same five wells where abstraction was monitored). Where present, boreholes drilled adjacent to dugwells as part of the project were monitored during the tests.

The tests were analysed using the BGSPT package (Barker, 1989) developed specifically for analysing large-diameter well tests. The package has two modules: a pumping-test fitting routine PTFIT; and a drawdown simulation routine PTSIM (referred to later in this report). The pumping-test data were modelled assuming the simplification of confined conditions. Under these conditions the model corresponds to the Papadopolous and Cooper (1967) equation for a large-diameter well. The estimation of storativity from the pumping-tests proved difficult with large confidence limits on values obtained. The storativity was therefore set to the value of specific yield of 0.05 obtained from the water balance. The values of transmissivity resulting from the tests are presented in Table 4.1. For some of the wells more than one test was carried out. Where this was the case the test that gave the best fit was chosen.

Table 4.1 Estimates of hydraulic conductivity from dugwell pumping-tests in the Pabal study area

Well	Transmissivity (m^2/d)	Saturated thickness (m)	Hydraulic Conductivity (m/d)	RMS error[1] (m)	Max. test drawdown (m)
98	78	1.5	52	0.264	1.40
99	2000	4.0	500	0.146	0.61
110	170	1.6	110	0.110	1.16
113	52	6.3	8.3	0.299	2.52
201	32	2.1	15	0.076	1.22

[1] root mean square errors between the observed drawdown during the test and the modelled drawdown

Despite the practical difficulties and limitations of these tests, the results are thought to reflect the heterogeneity of the aquifer system with the hydraulic conductivity. Apart from at well 99, these values of transmissivity are in broad agreement with previous estimates (Deolankar, 1980).

4.5 Modelling of near-well water-levels

The major objective of the case study was to identify the scale of the decline of the water-table across the aquifer. Two possible scenarios were considered; first, that the fall in water-level in the wells is due to dewatering of the aquifer in the vicinity of the well, and second, that the water-table declines throughout the aquifer relatively uniformly. To investigate this, the simulation program PTSIM was used to model the drawdown in the vicinity of the five pumping wells selected previously (nb. the simulated drawdown does not include the regional decline in water-level). Hydraulic conductivities obtained from the pumping-tests presented in Table 4.1, were combined with the saturated thicknesses of the amygdaloidal aquifer at maximum water-level, to obtain values of transmissivity. The specific yield of 5%, estimated from the water balance, was used. The pumping rates obtained from the monitoring of abstraction were input as monthly averages over the five month period from November to March.

The drawdown within the pumping wells and the surrounding aquifer, out to a distance of 200 m, was simulated (Figure 4.5). Table 4.2 shows the difference between the water-levels in the well and at a radius of 200 m. This is also shown as a percentage of the fluctuation of the water-table between maximum and minimum water-level in 1993/94.

Table 4.2 Simulated well drawdown and aquifer drawdown, 200 m from the well, compared with the annual well water-level fluctuation for 1993/94

Well	Difference in drawdown over 200 m (m)	1993/94 fluctuation (m)	Drawdown difference as a % of fluctuation
98	0.72	6.15	11.7
99	0.06	5.35	1.1
110	0.06	7.05	0.9
113	1.81	6.20	29.1
201	0.69	5.60	12.3

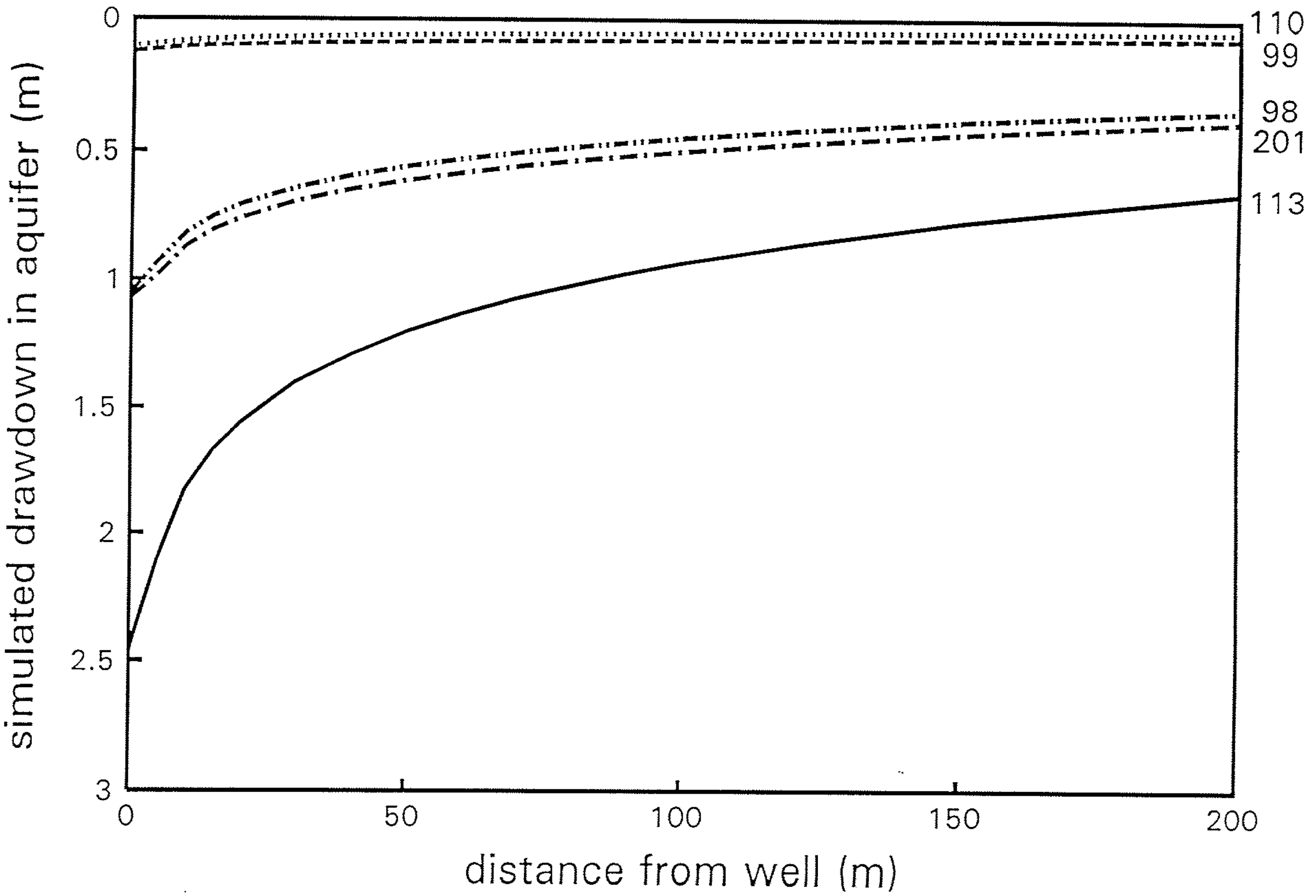


Figure 4.5 Near-well water-levels in 5 pumping wells in the Pabal study area, simulated using BGSPT

The relatively large drawdown in well 113 reflects the low value of hydraulic conductivity obtained from the pumping-test. However, the simulation of the other well abstractions suggest that the drawdown in the vicinity of the wells is not significant. Due to the assumptions made during the pumping-test analysis, this evidence is not conclusive; however, it does suggest that generally in this area the water-level fluctuations in wells can be considered to reflect the situation in the aquifer regionally.

4.6 Conclusions from the Pabal case study

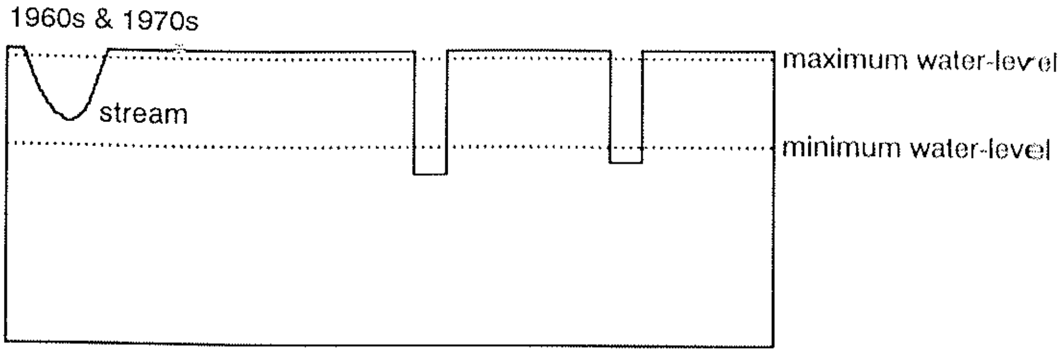
The results of this study show that the aquifer is extremely heterogeneous, with limited storage. Monitoring of abstraction and water-levels in the study area has shown that abstraction for irrigation is the major output from the groundwater system. Monitoring and modelling of near-well water-levels has indicated that the cones of depression associated with the irrigation wells are generally very shallow. The water-level in the aquifer as a whole is relatively flat, so the fluctuations seen in well water-levels reflect those in the aquifer. As many wells run dry or close to dry by the end of the dry season in a normal year, and, since many wells have reached the base of the productive aquifer, the groundwater system can be judged to be close to fully developed (Figure 4.6). The trend of declining groundwater levels with time has important implications:

- recharge to the aquifer is now at a maximum since no infiltration is rejected. This is because the water-table does not rise to the surface of the aquifer. In previous years, prior to the 1980s, when abstraction was significantly smaller, the water-table would rise to ground level, effectively preventing further infiltration,

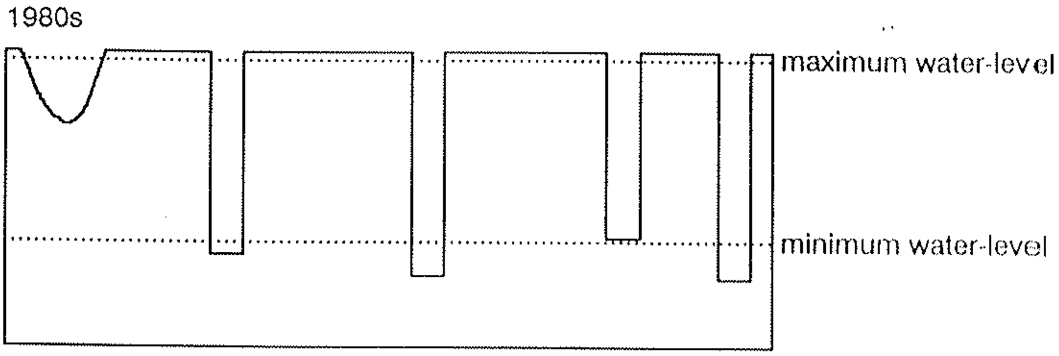
- the deeper post monsoon water-table (compared to previous years) reduces the groundwater contribution to streamflow (baseflow); anecdotal evidence suggests that surface water flowed for longer periods after the monsoon (in some until the end of February) than is currently the case.

The increase in recharge and the reduction in baseflow has ensured that more groundwater is available for abstraction. This largely explains how the considerable increase in groundwater abstraction over the past 20-30 years has been sustained.

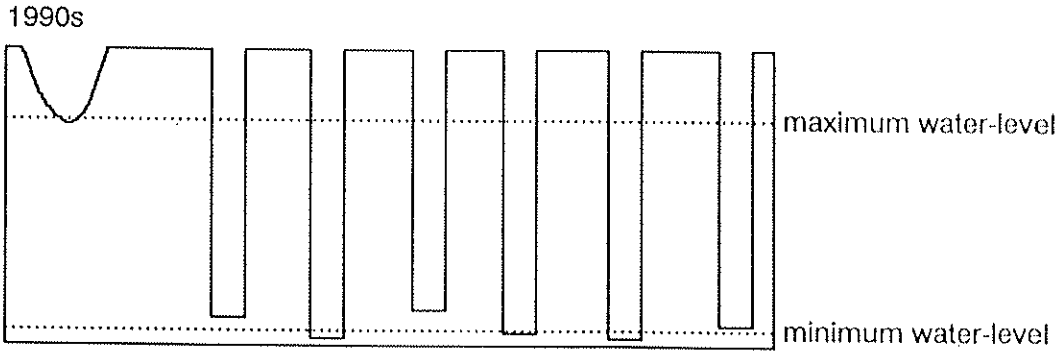
However, the consequence of the present situation is that a low rainfall year has devastating results. Low rainfall ensures reduced groundwater recharge and the poor rains mean that even the rainfed crops require significant quantities of supplementary irrigation. Thus even before the start of the main irrigation season (winter) the groundwater resources are already seriously depleted. In addition, there is little groundwater available later in the season for the irrigation of summer crops.



groundwater abstraction limited - animal powered mhots and diesel pumps
baseflow largest component of discharge
water-level rises to surface during monsoon preventing further infiltration



increase in groundwater abstraction - diesel and electric pumps and greater number of wells
discharge from aquifer increases and minimum water-level declines - wells deepened
water-level still rises to surface most years preventing further infiltration, but baseflow for less of dry season



substantial increase in groundwater abstraction - electric pumps and greater number of wells
further increase in discharge from aquifer, minimum water-level declines to base of aquifer - wells deepened
water-level no longer rises to surface, no rejected rainfall, baseflow for very limited period

Figure 4.6 Conceptual model of the evolution of the present groundwater system in the Pabal study area

5. Protection of drinking water supplies

Results of the Pabal case study show abstraction for irrigation to be the major discharge component of the catchment water balance. In Pabal, the diffusivity of the shallow weathered aquifer (the ratio of transmissivity and specific yield) is sufficiently large that the drawdown occurring in the irrigation wells significantly affects the water-levels throughout the aquifer (though some zones of low transmissivity aquifer do exist where steep cones of depression have developed around wells). This has implications for drinking water supplies as the significant decline in water-levels, due to pumping from irrigation wells, is likely to lower water-levels in public water supply wells. This chapter expands on the results of the case study to deal with interference effects under a range of aquifer parameters found in the Deccan basalts; it presents options for protecting drinking water supplies; and examines the effectiveness of one particular protection measure that has been adopted by Maharashtra State.

5.1 Modelling regional water-table decline due to abstraction for irrigation

To allow the results from the case study to be broadened to cover more comprehensively the range of aquifer properties that are found in the Deccan basalts, a brief modelling exercise was undertaken. The specific aim of the exercise was to show the spatial variation in drawdown of the water-table and in particular the drawdown in irrigation wells relative to the regional decline.

Regular grid model

The model adopted for this study is very simple (Figure 5.1). It consists of a regular and infinite grid of identical wells all pumping continuously. The assumptions made are that: the initial water-table is horizontal; the recharge is negligible after the start of pumping; and the transmissivity does not vary as the water-table falls. This last assumption is the least realistic simplification; it is most reasonable when flow is concentrated near the base of the aquifer. Well storage was ignored so that computations could be made on the basis of the Theis well function.

The drawdown was evaluated for points along a line as indicated by AB in Figure 5.1 (which over-emphasises well diameter). The parameters of the model that were kept fixed for all model runs are given in Table 5.1.

Table 5.1 Parameters for the well grid model

Well separation	300 m
Well radius	2.5 m
Pumping rate	71.4 m^3/d

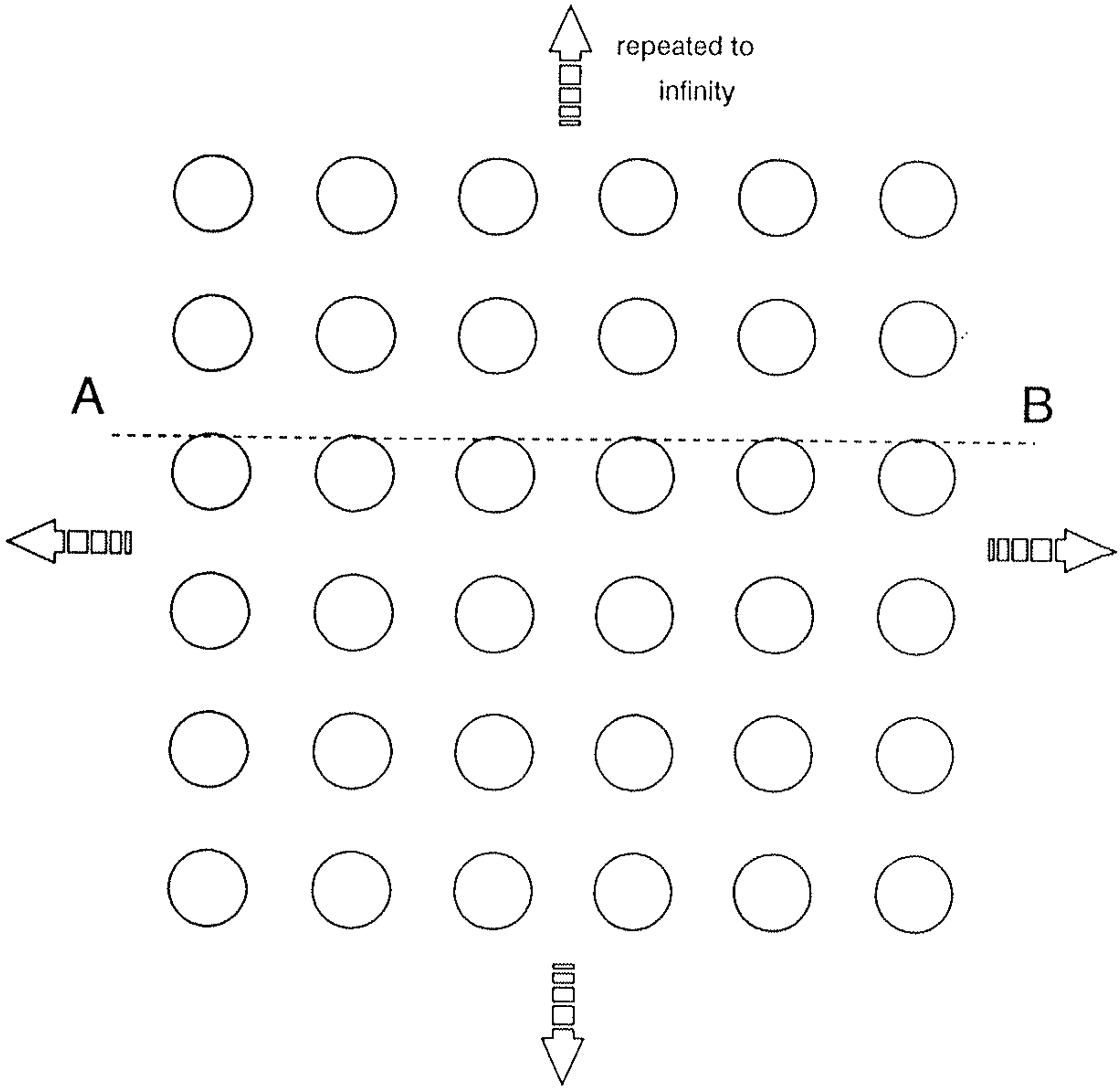


Figure 5.1 Regular grid model

Six runs of the model were performed using three specific yields and four transmissivities (Table 5.2), covering the range of values quoted for the Deccan basalts (Deolankar, 1980). The drawdown distribution along line AB after 250 days was computed. (NB. with this model drawdown will be proportional to time as transmissivity does not vary with depth.)

Table 5.2 Diffusivities (T/S_y in m^2/d) and corresponding run numbers for combinations of specific yield and transmissivity

Specific Yield	Transmissivity (m^2/d)			
	20	50	100	200
1%			10000 *run 5*	
5%	400 *run 1*	1000 *run 2*	2000 *run 3*	4000 *run 4*
10%			1000 *run 6*	

The regional drawdown in the aquifer is independent of the transmissivity. Table 5.3 shows how the regional drawdown varies with the three values of specific yield chosen.

Table 5.3 The regional drawdowns (in metres) as a function of specific yield

Specific yield	Regional drawdown (m)
1%	19.83
5%	3.97
10%	1.983

Figure 5.2 shows how the water-level in the model varies along the line AB for the four transmissivities, with the specific yield of 5% (runs 1-4). Figure 5.3 shows how the water-level varies along the line AB for the three specific yields with a transmissivity of 100 m^2/d. Some general conclusions from the model results are presented here.

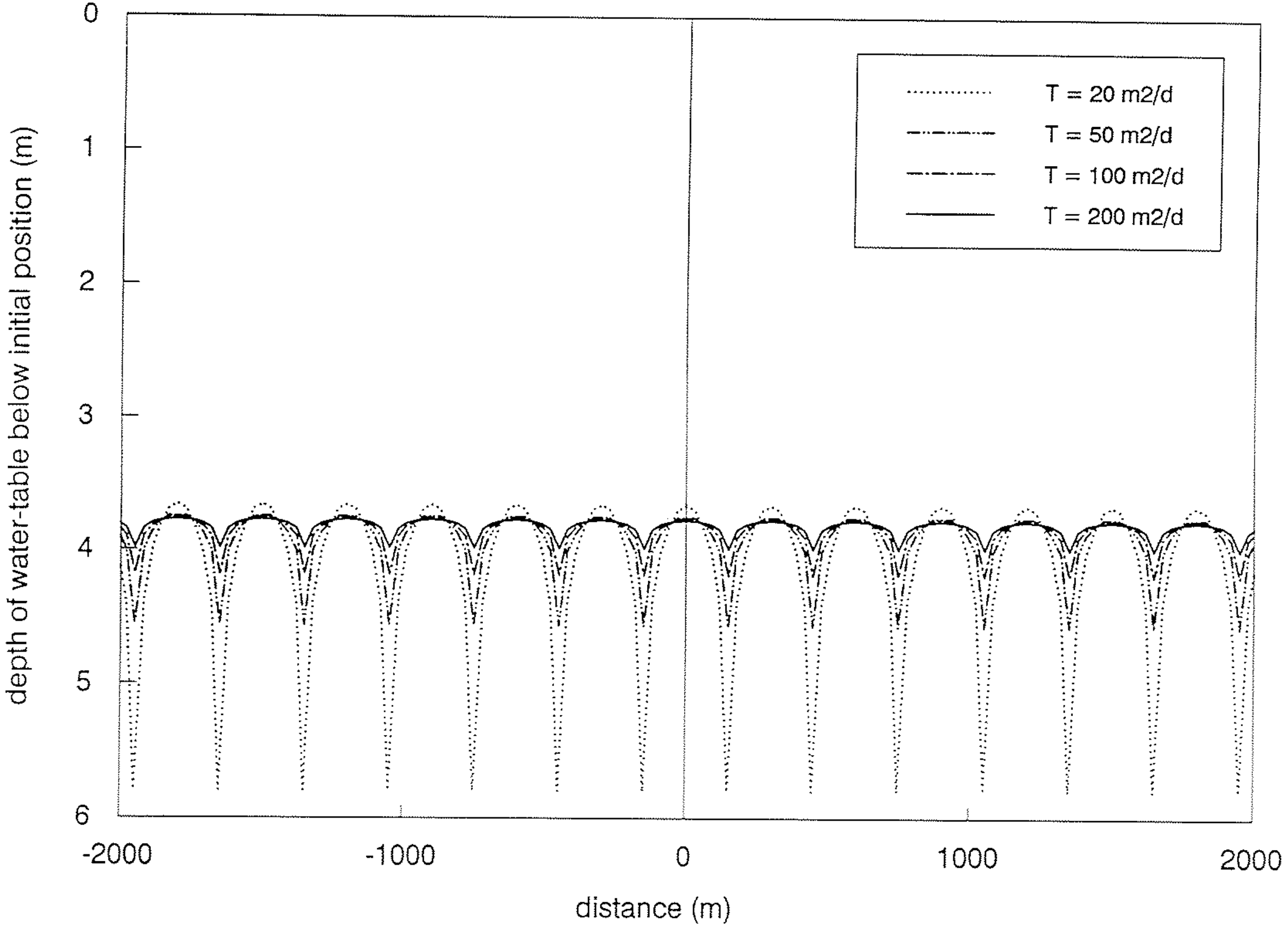


Figure 5.2 Drawdown along cross-section AB of the regular grid model, after 250 days pumping, for range of transmissivities (specific yield 5%)

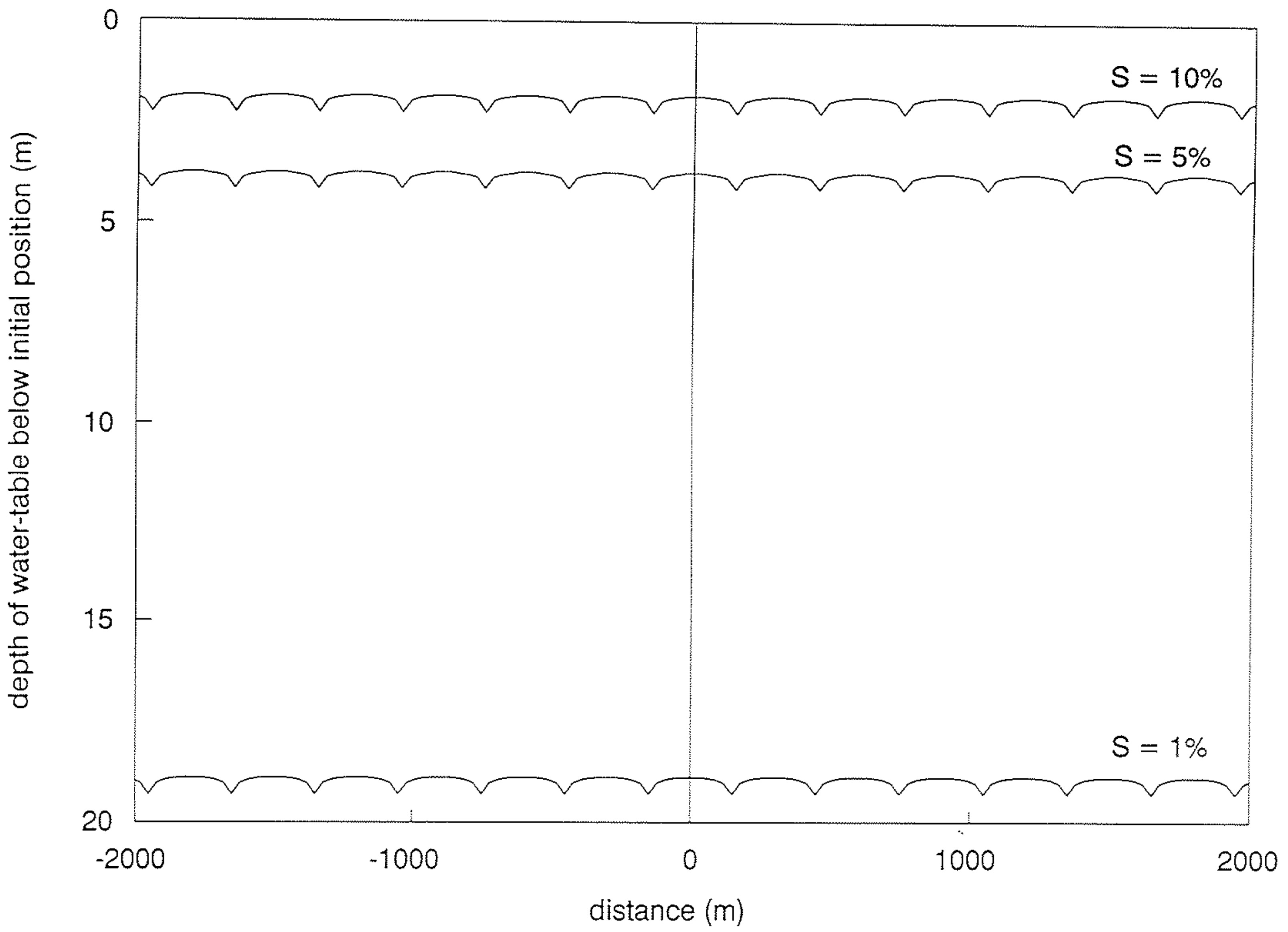


Figure 5.3 Drawdown along cross-section AB of regular grid model, after 250 days pumping, for range of specific yields (transmissivity 100 m^2/d)

1. The drawdown in the irrigation well relative to the regional decline increases as the transmissivity decreases, but only becomes significant at the minimum of the range of transmissivities. At the minimum transmissivity of 20 m^2/d the drawdown in the well is approximately 150% of that in the aquifer as a whole. However, in reality, in aquifers of low transmissivity, it is necessary to use lower abstraction rates to avoid dewatering the well prior to the end of the dry season and therefore the regional drawdown will be limited.

2. Over most of the range of transmissivities the drawdown in the irrigation wells is similar to the regional decline in the water-table. As a result abstraction, which invariably continues until water-levels are at the base of the irrigation wells, will cause the regional water-table, and hence also the water-level in public supply wells, to fall significantly.

3. The drawdown of water-levels in irrigation wells, and in the aquifer regionally, increases significantly as specific yield decreases (Figure 5.3). This shows the importance of obtaining accurate values of specific yield for modelling purposes.

The results from the model illustrate how the drawdown in the irrigation wells *relative to* the regional decline depend on the aquifer diffusivity; compare runs 2 ($T=50\ m^2/d$, $Sy=5\%$) and 6 ($T=100\ m^2/d$, $Sy=10\%$) which both have a diffusivity of 1000 m^2/d. However, the regional decline will depend on the specific yield of the aquifer, again illustrated by runs 2 and 6.

Grid model with missing wells

The model up to this point has had a regular grid of wells extending to infinity. A more realistic model of rural conditions should include locations where irrigation wells are absent due to the existence of more densely populated village areas. These areas are important as it is within the villages that public supply wells are often situated. The model was developed to show the shape of the water-table across an area from which a number of wells (four in this case) had been removed (Figure 5.4). A number of runs of the model were carried out with the same input parameters and range of aquifer properties as with the previous model.

The effect of removing the wells can be seen in Figure 5.5. This compares the water-table variation along the line AB, with and without the removal of the four wells, for three times, 50, 150 and 250 days. A mound develops around the central point, becoming relatively larger with time. The village is acting as a protection zone from the effects of the surrounding irrigation wells. Figures 5.6 and 5.7 show the results of the runs of the model with the missing wells. The size of the mound is dependent on the diffusivity of the aquifer, with a larger mound occurring where the diffusivity is smaller. However, the mound would only appear to be significant at the lowest end of the range of diffusivities suggested for the Deccan basalts. In addition, though abstraction for irrigation does not occur within these areas, the population is concentrated here and therefore the abstraction for public supply will be greater. The analysis of zones of limited abstraction will be developed further in section 5.3.

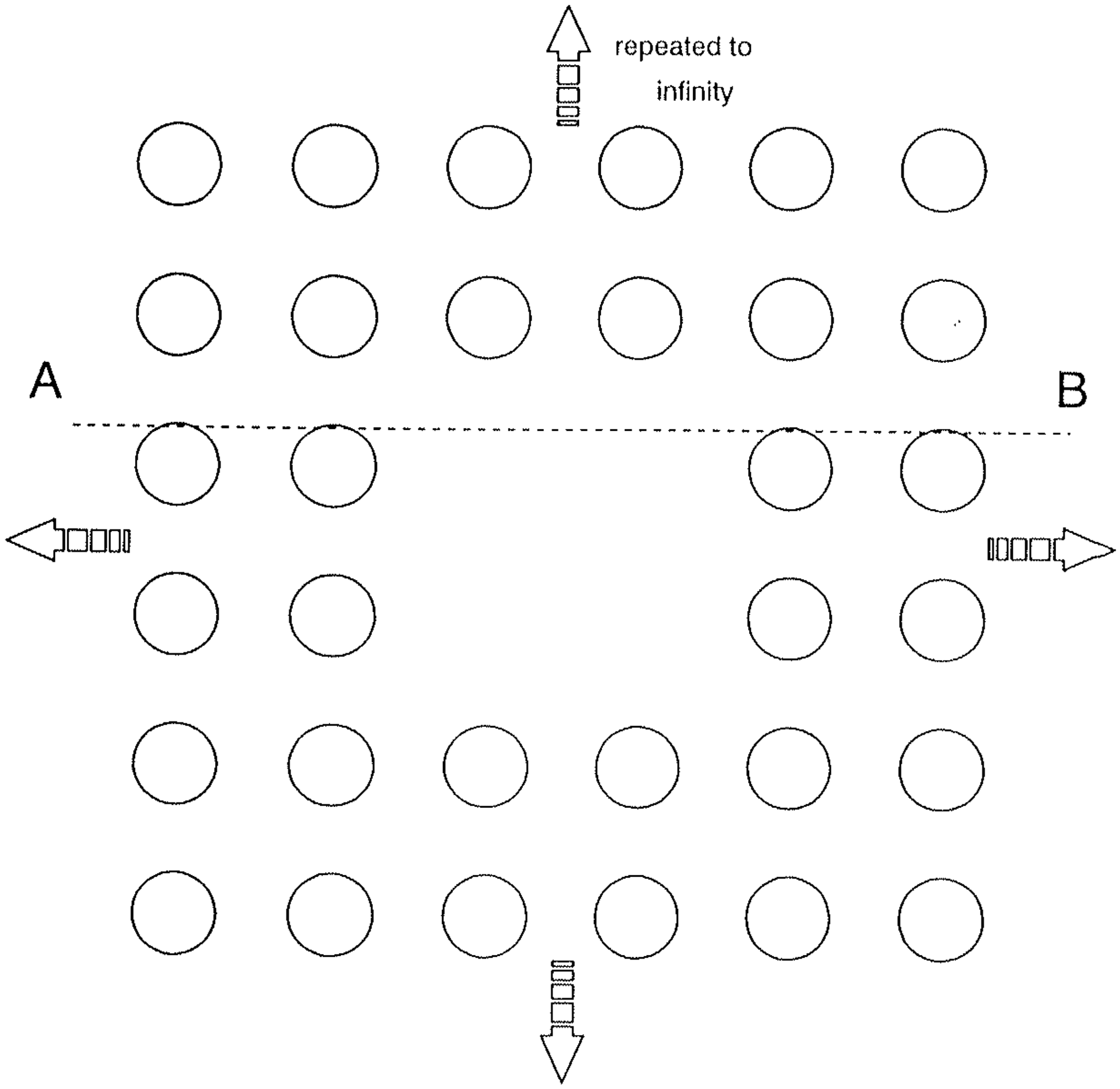


Figure 5.4 Regular grid model with missing wells

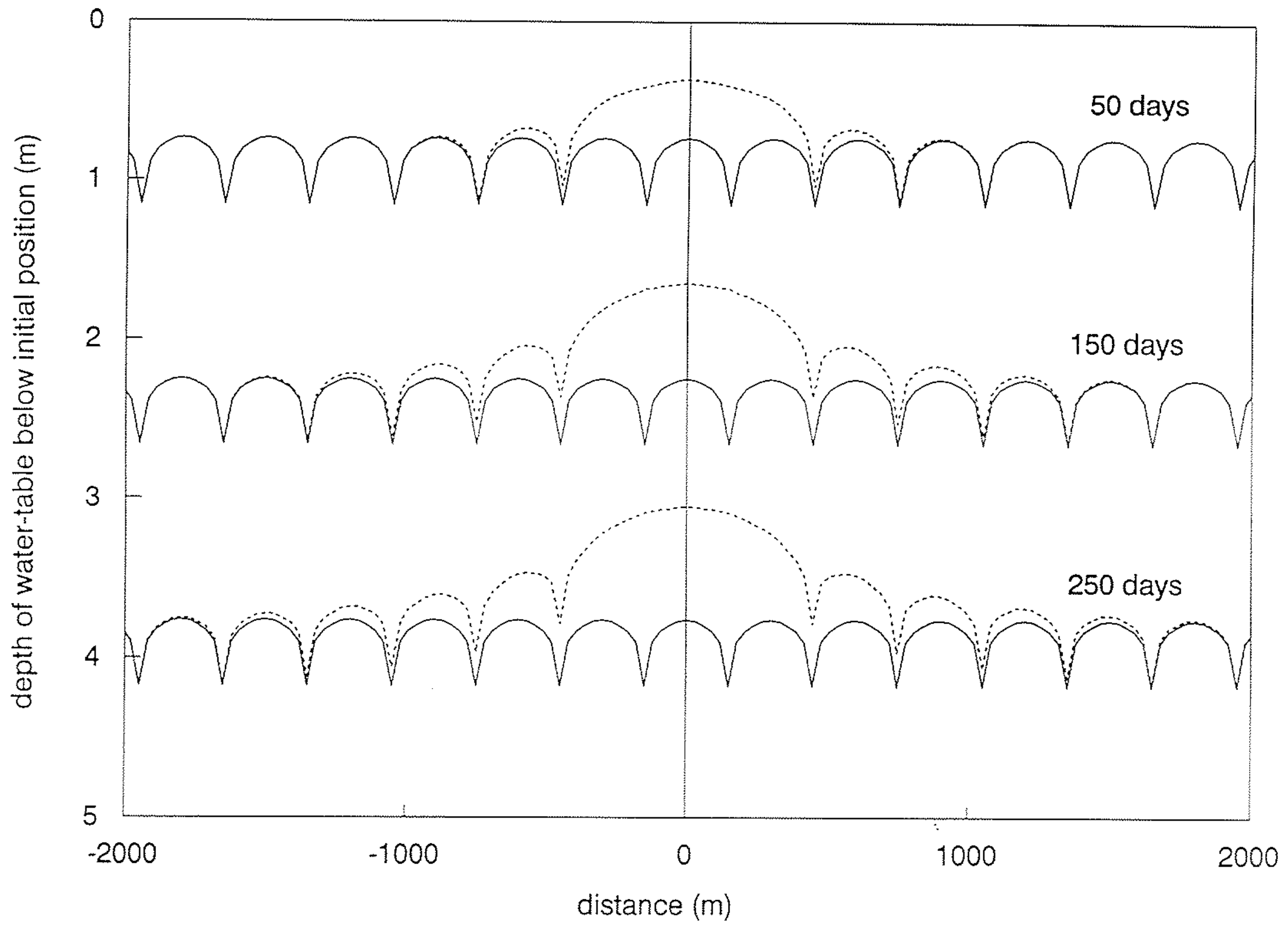


Figure 5.5 Comparison of the development in time of the drawdown along a cross-section AB of regular grid model and regular grid model with 4 central wells missing (specific yield 5%, transmissivity 100 m^2/d)

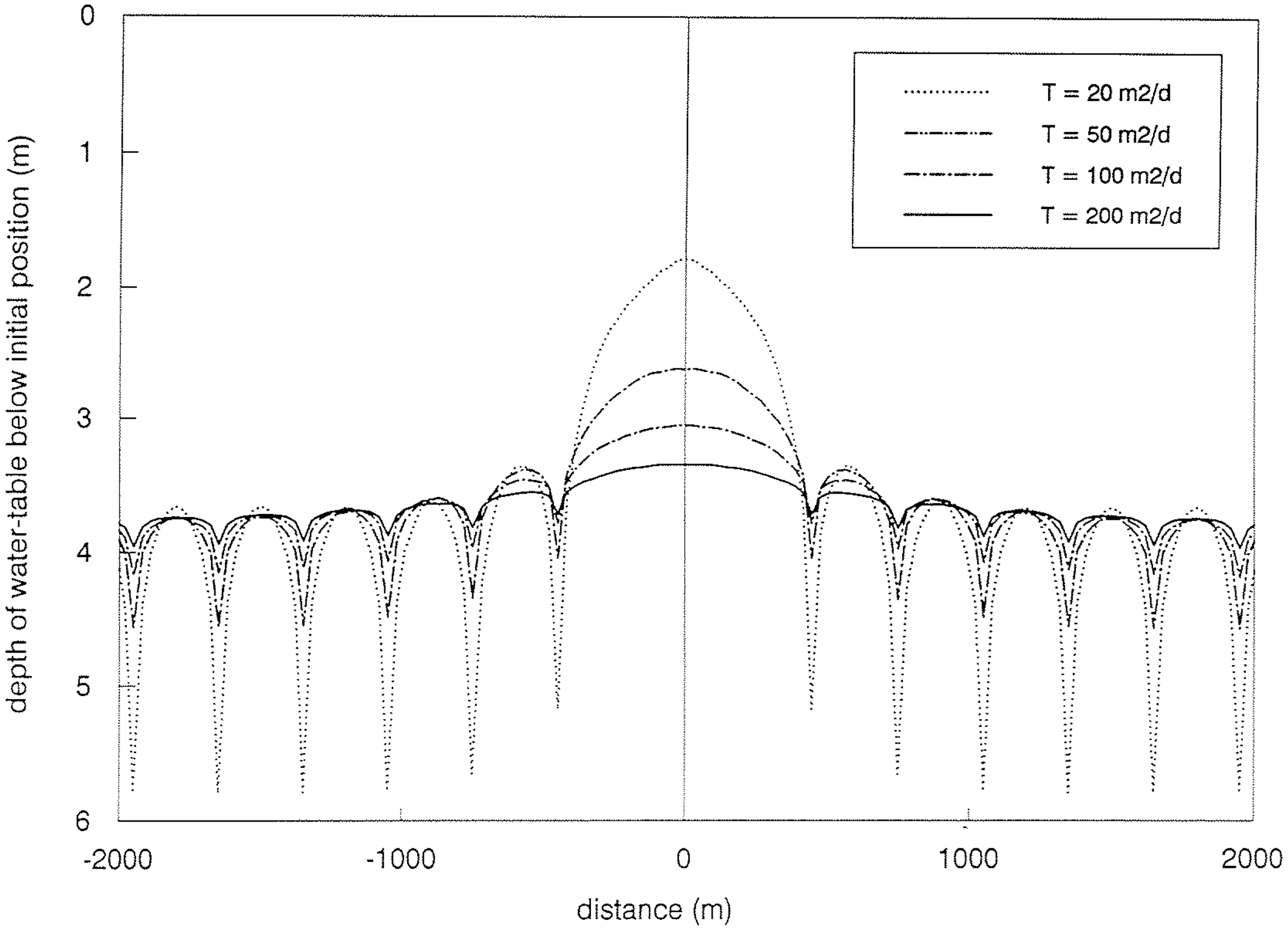


Figure 5.6 Drawdown along cross-section AB of regular grid model with 4 central wells missing, after 250 days pumping, for range of transmissivities (specific yield 5%)

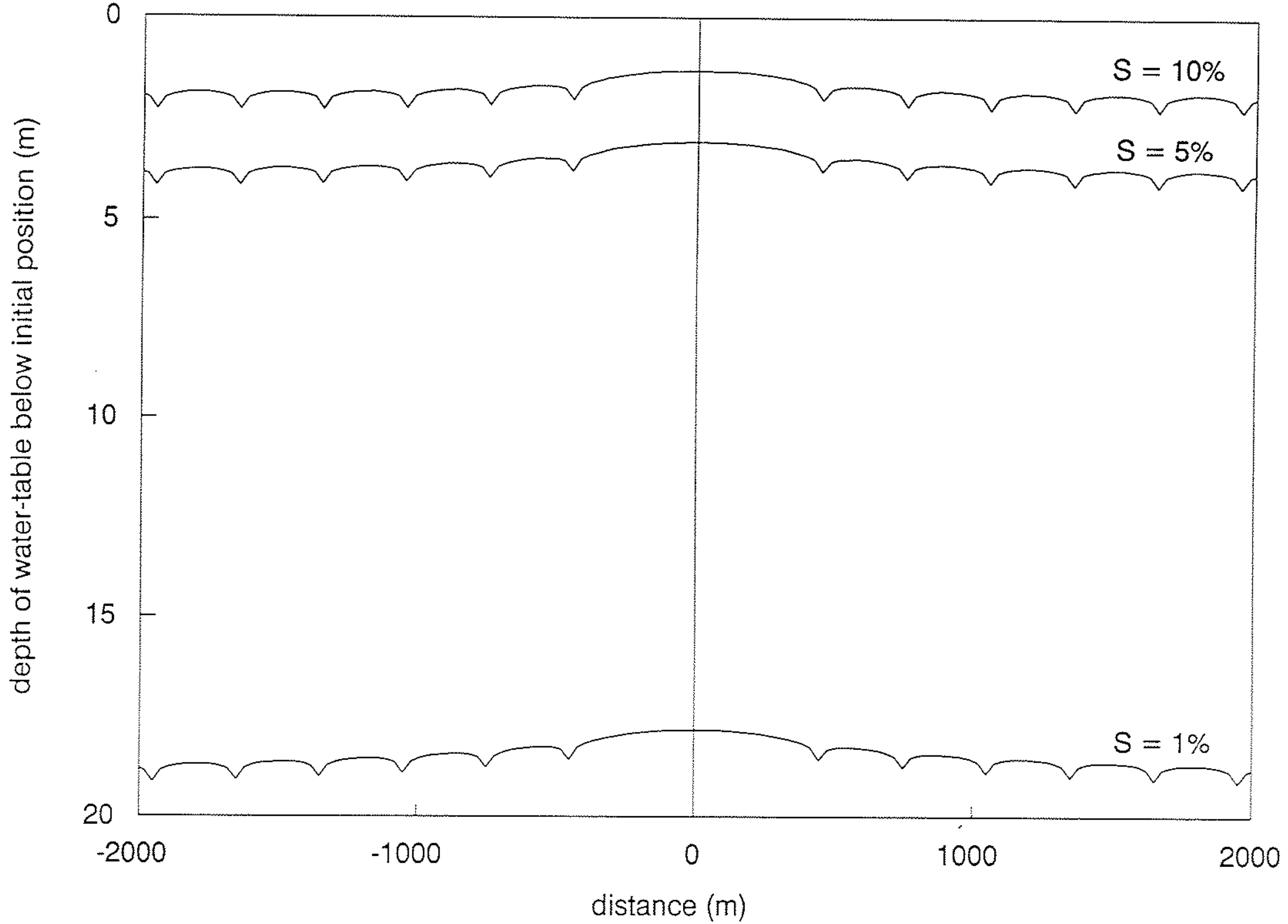


Figure 5.7 Drawdown along cross-section AB of regular grid model with 4 central wells missing, after 250 days pumping, for range of specific yields (transmissivity 100 m^2/d)

Conclusions

Though this modelling exercise has limited the range of input parameters used (average abstraction rate, well spacing and well diameter), it has illustrated the variation in drawdown that can occur in the Deccan basalt aquifers. It has shown that across much of the range of diffusivities found in this type of aquifer, the drawdown occurring in irrigation wells is not significantly different to the regional water-table decline. Therefore, the existence and potential for serious overexploitation of the aquifer has been identified.

5.2 Options for protecting drinking water supplies

The evidence of the likely detrimental impact on drinking water supplies due to the abstraction of groundwater for irrigation has been presented. The implication is that controls are needed to limit abstraction. These controls may be **direct** ie. by limiting the amount of groundwater that can be abstracted, which may necessitate legislation. Some possible options are presented in Table 5.4. These options can either limit the further development of groundwater resources or reduce abstraction from existing sources. It is more realistic to instigate measures to carry-out the former of these options. In both cases the efficiency, application and ease of policing these or any other measures may be questionable.

Table 5.4 Options for controlling groundwater abstraction

Control		Physically possible		Potentially effective	Rural Acceptance		Policeable	Comments
		Existing	New		Existing	New		
Well design	depth	y	y	y	n	y	y	protect shallow and deep aquifers
	diameter	n	y	?	n/a	y	y	model to check viability
Pump	type	y	y	y	n	y	y	
	number per well	y	y	y	n	d	d	multi-ownership difficulties
	intake position	d	y	y	d	d	d	
Well abstraction	duration	d	y	y	n	d	d	control through electrical supply, pump type and co-operative user groups
	rate	d	y	y	n	d	d	
Location in relation to public supply well		d	y	?	n	d	y	example - protection zones

y - yes, d - doubtful, n - no, ? - needs further research, n/a - not applicable

Other controls may be **indirect** ie. the introduction of measures that reduce the need for water. Such measures might include changes in agricultural practices such as the use of more efficient irrigation methods, or the move to crops with a lower water requirement. However, in general, these are long-term measures.

One option that in some communities and physical settings may have merit is the *user group* (Moench, 1992). Where a community recognises the impact of overexploitation on the sustainability of their groundwater resource they may join together to manage the resource. Any necessary reduction in the level of exploitation is agreed within the community rather than being implemented from outside and hence is more likely to succeed. Such a method may use both direct and indirect measures. A user group experiment undertaken in Pune District, in Maharashtra State, by an organisation called 'Pani-Panchayat' has shown encouraging results. However, with all measures, even user groups, equitability may be questionable as the section of the population most likely to suffer from a control on groundwater abstraction could be the poor.

The issue of measures for safeguarding groundwater resources is a complicated one and no evidence has been found by the authors of effective methods that have so far been applied in regions where sustainability is a problem. The issue is not addressed comprehensively here but one option, recently implemented in Maharashtra State, is discussed as an example.

5.3 Effectiveness of protection zones

Maharashtra State legislation

In 1993 Maharashtra State introduced legislation to protect public groundwater supplies. The legislation is described in Box 1. It aims to reduce the drawdown in the water-level in public supply wells due to the abstraction from surrounding irrigation wells. As yet no examples have been obtained of the application of this legislation.

Though the Maharashtra State Government is to be commended for addressing the problems of overexploited groundwater resources, the results of field monitoring and initial modelling work, presented in this report, suggest that the setting-up of protection zones around public supply wells may not always be effective. To investigate the aquifer conditions under which the protection zones may or may not be effective, further modelling was undertaken.

Modelling protection zones

The model used to evaluate the protection zones was introduced by Barker *et al.* (1991). This model is a simplification of the model used in section 5.1. However, it retains the essential aspects of that model while allowing more flexibility in varying and comparing the results of a range of input parameters and hence enabling greater insight. (NB. the model does not have the capability to model the complexities of individual sites but will help to indicate where more sophisticated modelling is required.)

Box 1

Summary of Maharashtra Act No.XXVIII, 1993.

'An act to regulate the exploitation of groundwater for the protection of public drinking water sources and matters connected therewith and incidental thereto.'

Definitions
Public drinking water sources (PDWS) - wells used for 'drinking or other domestic matters' and for cattle

Well - dugwell, borewell, dug-cum-borewell, tubewell and filter point

Maharashtra state government representative (MSGR) - referred to as the 'Collector'. He acts on the advice of the 'Technical Officer' who is from the Central Ground Water Board (national organisation) or the Groundwater Surveys and Development Agency (state organisation).

Legislation
No one may sink a well within 500 metres of a PDWS, though permission may be obtained from the MSGR if they are satisfied it would not adversely affect the PDWS. Abstraction from such a well is under the control of the MSGR.

The MSGR may at any time during the monsoon or after declare an area as a 'water scarcity area' (WSA) depending on the 'quantum and pattern of rainfall'. This declaration can last for a period of up to a year. During that time a one kilometre protection zone may be set-up around a PDWS. Within this protection zone water may only be abstracted for drinking and domestic purposes though wells may be used for the irrigation of existing crops with the permission of the MSGR. Priority for the use of water for irrigation of existing crops will be given first to those wells situated furthest from the PDWS.

If a surface water catchment is declared an overexploited watershed (OW) then no-one can sink a well in that catchment without the permission of the MSGR. An overexploited watershed is defined as a watershed where the 'estimated annual groundwater extraction is more than 85 per cent of the estimated average annual groundwater recharge'. Abstraction from an existing well in an OW may be prohibited during the six months period from 1 February to 31 July.

The legislation allows the MSGR to conduct pumping-tests and install water-level recorders and flowmeters on wells and carry-out geophysical surveys in their vicinity, as part of their investigations.

The model approximates the drawdown at a central point due to the abstraction of irrigation wells surrounding it. For this exercise it is assumed that a public supply well is located at the central point. The model replaces the abstraction from the individual irrigation wells by a uniformly distributed abstraction. A circle is set around the central point within which no abstraction occurs; this circle is analagous to the area of settlement that often exists around a public supply well and within which no irrigation takes place. The uniform abstraction distribution stretches out from this inner boundary to an outer boundary, which in Deccan basaltic regions may coincide with the edge of the cultivated area, where the compact basalt hills begin. It is assumed that no recharge takes place during the period over which the model is run, which in the following example has been set to 250 days, similar to the period of a dry season.

The model allows the drawdown at the central point due to the surrounding wells to be approximated, with and without the introduction of a protection zone. It models the protection zone by assuming the abstraction increases by some factor outside of the protection zone but remains unchanged within the zone. This corresponds to the situation where a ban on new wells and an increase in abstraction, within the protection zone, is enforced. The overall abstraction increases outside of the protection zone due to an increase in well density and/or the average abstraction per well. The effectiveness of the protection zone is measured by the ratio of the drawdown at the central point with and without the protection zone. Figure 5.8 shows a plot of this ratio against aquifer diffusivity for a number of protection zone radii. (NB. the model does not take into account the drawdown due to abstraction from the central public supply well.) The parameters kept constant in the model are given in Table 5.5. For further description of the model and the results obtained from it see Macdonald *et al.* (1995).

Table 5.5 Parameters for protection zone model

inner boundary to abstraction	100 m
outer boundary to abstraction	3000 m
period of model run	250 days
increase in abstraction	20%

The results of this modelling exercise show that the improvement due to the introduction of protection zones is greatest where the diffusivity is least, and when a large protection zone radius is used. However, as Figure 5.8 shows, even with a protection zone radius of 1000 m and a diffusivity of 400 m^2/d the introduction of a protection zone only reduces the drawdown that would have otherwise occurred in the public supply well due to irrigation by 36%. Further, where diffusivity is low the overall regional decline is likely to be small and so the absolute improvement due to a protection zone will not be great. This analysis raises doubts as to the general effectiveness of protection zones within the Deccan basalt environment.

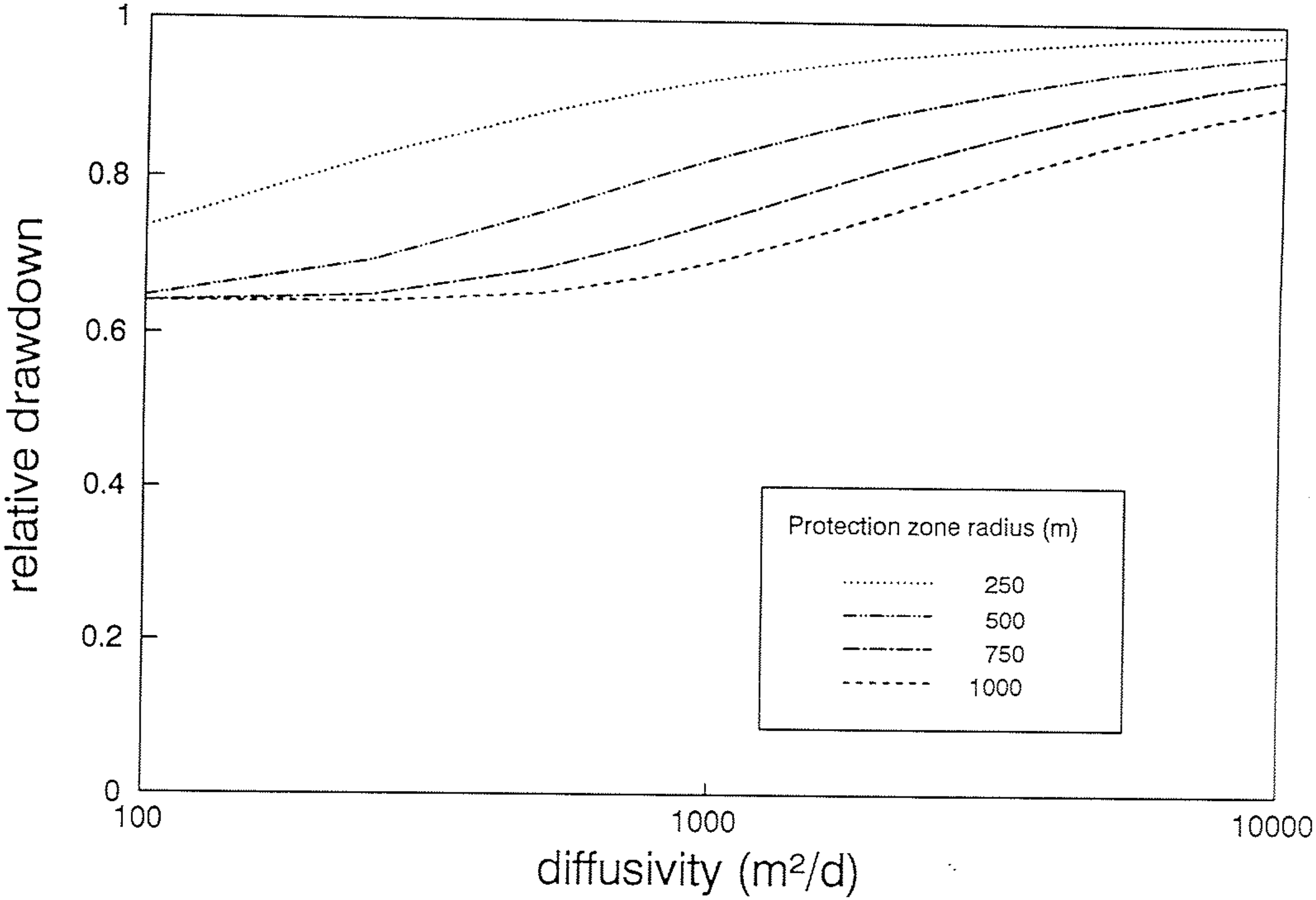


Figure 5.8 Drawdown in a central well with a protection zone relative to the drawdown without a protection zone, for a range of diffusivities and a number of protection zone radii

6. Discussion

6.1 Implications for sustainable development of groundwater resources

This discussion is based on the general situation in the Deccan Basalts, but refers to the conclusions from the Pabal case study. In many of these areas groundwater appears to be fully utilised, or at least as close to being fully utilised as is practical. Water-levels at the end of the dry season are close to the base of the aquifer although it appears that most community wells still have sufficient water to meet the minimum water supply requirement prior to the onset of the monsoon. Whilst in 'normal' rainfall years the shallow aquifer is likely to be replenished, serious water shortages, including the 'drying-up' of community wells, are likely whenever there is a 'failure' of the monsoon.

Further sinking of shallow irrigation wells is likely to cause greater interference with existing irrigation wells. The water-table will decline more rapidly although the total quantity pumped will not be any greater, since that quantity is limited by the water-table approaching the base of the shallow aquifer system.

There must be concern that some farmers when faced with this situation will deepen their wells to tap the underlying aquifer, where present. This would almost inevitably lead to substantial leakage from the shallow aquifer and result in many shallow wells drying up for many months of the year. More wells would then be deepened and this increased abstraction from deeper layers would drive the water-table down even further.

Such unregulated competition for water resources by the farmers would simply result in 'chasing the water-table'; in this situation the poor in the community, unable to afford the cost of deepening their wells, would suffer the most (Moench, 1992). It must be stressed that boreholes that penetrate to deeper confined aquifers do not tap new water resources (since the bulk of the recharge to these deeper aquifers comes from the shallow layers) but simply compete for a finite resource. Such a situation has been described for the hard-rock aquifers in some districts of Tamil Nadu State. Dug-cum-bore wells and boreholes used for irrigation have been drilled to depths in excess of 50 m. This has led to the water-table declining from 10 m to 50 m during the past 40-50 years whilst the area irrigated by each well has reduced from 1.5 ha to less than 1 ha (Sivanappan, 1991).

For sustainable development of groundwater resources, exploitation of deeper aquifers for irrigation should be avoided, except where it can be demonstrated that recharge to these aquifers is considerable and does not occur as leakage from shallower groundwater. Deeper aquifers should be reserved for emergency drinking water supplies.

6.2 Implications for policy

The problem of declining groundwater levels in many areas of India, mentioned previously in this report prompts the question 'why is overexploitation of groundwater allowed to happen?'. There are several reasons:

1) Lack of knowledge of groundwater resources

There is insufficient knowledge of the recharge to, and storage within these hard-rock aquifers; recharge estimates are often based on values obtained from different hydrogeological environments or derived from inappropriate rainfall-recharge relationships. Groundwater resources may as a consequence be wrongly estimated.

This problem is exacerbated by (a) the complexities and inhomogeneities of hard-rock aquifer systems and (b) the understandable pressure to develop groundwater resources, often at the expense of detailed investigations and/or monitoring.

2) Uncertainty of the precise causes of water-level fluctuation and trends

The vast area of India means monitoring networks are often too sparse to give an accurate picture of the pattern of the water-table fluctuation and its relation to abstraction, which may be localised (over km^2 rather than 10s of km^2). Further, long-term water-level trends are often difficult to 'pick out' given the significant natural fluctuation due to drought periods.

3) Inability to control abstraction

Once a problem is realised it is then very difficult to control abstraction because well usage is already established and there is a need to recover the cost of investment in wells, pumps etc through high water-use cash crops.

The problem of excessive groundwater exploitation is often localised (i.e. village level) and is likely to develop where the groundwater potential is greatest. This is because once well yields are proven, farmers will often invest their own funds in well construction when soft loans are unavailable, due to existing excessive exploitation in the area.

4) Inappropriate incentive schemes

Incentive schemes are often designed to promote groundwater development rather than water conservation. Subsidies on electricity have made it economical for farmers to run high-powered pumping systems that allow large quantities of groundwater to be abstracted. Further, it has been suggested that the magnitude of groundwater recharge may have been overestimated in some areas, resulting in the support for programmes of development of well irrigation that are not sustainable (Dhawan, 1995).

6.3 Future needs

It is recognised that irrigation by dugwells in the hard-rock areas of India has made a major contribution to food production in these localities. However, it is important to realise that groundwater is a finite resource and that in some areas of India, exploitation of this resource already exceeds recharge. Such a situation is not sustainable. It results in increased pumping costs; the drilling of deeper wells; reduced well yield and thus an increase in the unit cost of water; and the 'drying-up' of community wells.

However, it is also true, given the limited storage within the aquifer and the not-infrequent failure of the monsoon, that short-term reductions in yield will always be a problem. It is therefore unrealistic, and almost certainly makes poor economic sense, to restrict the level of groundwater development such that irrigation wells never run dry. Protection of community drinking water wells should, however, be considered as a priority for an aquifer management policy.

The problem of overexploitation of groundwater resources in these hard-rock areas is a consequence of the lack of effective groundwater management. Current controls (with the exception of recent Maharashtra State Government legislation) on groundwater abstraction appear to be limited to withholding loans from farmers to pay for new well construction, or for pumps in areas considered to be either close to or already fully exploited. However, in these critical areas the richer farmers are often willing to deepen wells, drill boreholes and install pumps at their own expense without a 'soft loan'.

Effective management requires (i) a good understanding of the aquifer system and the quantities of water pumped out by irrigation wells, and (ii) the ability to control abstraction. The latter requirement needs either a controlling mechanism that is both easy to police and enforce, or that the well users participate in the management of the aquifer and are willing to curb abstraction as necessary. The latter option is preferred since policing and controlling groundwater abstraction without the co-operation of the users is extremely difficult in practice.

The success of well-users associations or co-operatives depend on the farmers having faith in the estimate of groundwater potential made by the state government's groundwater agency and the fairness of the agency in any arbitration on disputes that are bound to arise between users.

As such, there is an urgent need to put more resources into groundwater resource assessment, with emphasis on improved recharge estimates, specific yield determination and detailed monitoring, especially in critical areas. In these areas it is important both to monitor groundwater and surface water and to obtain accurate records of number of wells, their yield and the area irrigated, in order to compute current groundwater withdrawal. Detailed pilot studies in critical areas with differing hydrogeological environments are recommended. Such investigations could be undertaken by CGWB, State Governments and Universities, with funding from Central or State Government, NABARD or aid agencies.

In areas where significant groundwater depletion has already occurred it will be much more difficult to remedy the situation since causal factors are usually well entrenched. Measures such as significant reduction in groundwater abstraction are likely to be very unpopular. However, a policy for protecting water resources in areas where serious depletion has not occurred should be much easier.

A key management strategy must be to restrict the depth of wells and to reserve deeper aquifers, where they exist, for emergency potable supplies only. In areas where deeper aquifers do not exist, protecting community wells by a 'no pumping zone' is an obvious option. However, results from this study suggest that such zones need to be large. This may mean that pumping from all irrigation wells may have to be strictly curtailed for the policy to be effective; a drastic option but at least one that should be considered fair!

The policy of extending loans to encourage greater groundwater abstraction should be discouraged, except in those areas where the level of utilisation is known to be very low; instead loans might be better directed towards water conservation schemes. Such schemes could include the installation of check dams, the construction of recharge tanks, the use of drip irrigation and the growing of less water-demanding crops.

7. Conclusions

The groundwater system in the Pabal study area is believed to be typical of many areas of the Deccan basalts. The conclusions from this study are as follows:

1) The shallow aquifers within the Deccan Basalts are the largest groundwater resource. In areas where recharge to deeper aquifers is derived by leakage from the shallow aquifer the abstraction from the deeper aquifers is likely to result in the widespread lowering of the shallow water-table. Whilst the use of deep boreholes might be considered as a logical progression in the development of these aquifers this should be generally avoided because of the serious impact on the shallow water-table. Very little is still known about the hydrogeology of the deeper aquifers of the Deccan Basalts.

2) There is evidence that a significant increase in groundwater abstraction has caused a general lowering of the water-table. This has three important consequences:

    a) recharge to shallow groundwater has increased because the available storage within the aquifer has increased,

    b) the baseflow contribution to streams has decreased,

    c) wells are more susceptible to drying-up during drought periods.

3) The reduced baseflow contribution to streams, if reproduced over large areas may result in decreased volumes of water in perennial rivers downstream.

4) Currently the available storage in the shallow aquifer at the end of summer, following normal monsoon rains, is limited. Failure of the subsequent monsoon would inevitably result in severe water shortages including village water supplies.

5) The decline in the water-table is consistent throughout the aquifer and is only seldomly restricted to localised zones around the main abstraction wells. Irrigation wells can therefore cause significant water-level decline in community water supply wells.

6) The protection of drinking water supplies must be seen as a priority.

7) Legislation to protect village drinking water supplies by reserving deeper aquifers in the Deccan basalt for emergency supplies only, should be considered.

8. Recommendations

Research is urgently required to provide a scientific and socio-economic framework for a groundwater management policy in the hard-rock areas of India.

This research needs to:

(i) evaluate the groundwater system in various hard-rock environments and in particular, to quantify recharge to, and abstraction from, the aquifer; determine the hydraulic characteristics of the aquifers and the variation regionally; quantify the baseflow/groundwater level relationship; and monitor groundwater levels for indications of temporal trends.

(ii) identify and assess the effectiveness of various management options to both control groundwater abstraction and protect drinking water supplies.

(iii) evaluate socio-economic implications of various options in (ii) above and rank these options in terms of their acceptability to users of groundwater resources; their equitability; and the practicalities of their implementation and enforcement.

It is envisaged that this type of research would be best undertaken as a series of pilot studies in representative hydrogeological and socio-economic environments. It is important that these pilot studies are combined with existing regional monitoring (possibly supplemented by additional monitoring where gaps exist) to ensure that a broader picture can emerge from these more detailed studies.

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