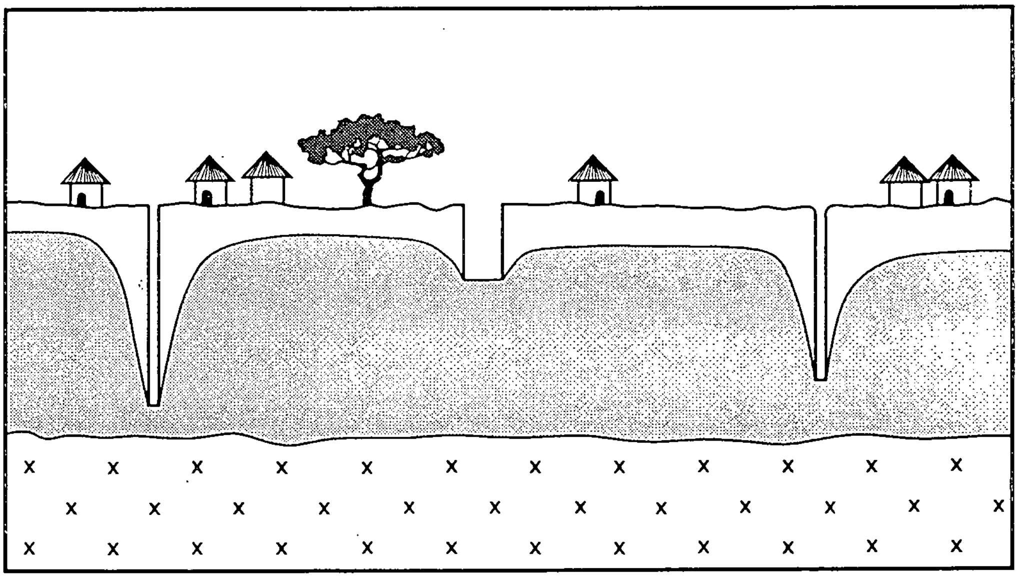
British Geological Survey

TECHNICAL REPORT WC/97/1
Overseas Geology Series

SIMPLE MODELLING TO ILLUSTRATE THE IMPACT OF DROUGHT ON GROUNDWATER AVAILABILITY

A M MacDonald and D M J Macdonald



Natural Environment Research Council

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

British Geological Survey

TECHNICAL REPORT WC/97/1
Overseas Geology Series

SIMPLE MODELLING TO ILLUSTRATE THE IMPACT OF DROUGHT ON GROUNDWATER AVAILABILITY

A M MacDonald and D M J Macdonald

This document is an output from a project funded by the UK Overseas Development Administration (ODA) for the benefit of developing countries. The views expressed are not necessarily those of the ODA

ODA classification :
Subsector : Water and Sanitation
Theme : W1 - Improve integrated water resources development and management, including systems for flood and drought control
Project title : Groundwater management in drought-prone areas in Africa
Project reference : R6233

Bibliographic reference :
MacDonald A M and others 1997. Simple modelling to illustrate the impact of drought on groundwater availability
BGS Technical Report WC/97/1

Keywords :
Groundwater, modelling, drought, water availability

Front cover illustration :
Schematic showing cones of depression in the water table around abstracting wells

Keyworth, Nottingham, British Geological Survey, 1997

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desk at the Survey headquarters, Keyworth, Nottingham. The more popular maps and books may be purchased from BGS-approved stockists and agents and over the counter at the Bookshop, Gallery 37, Natural History Museum, Cromwell Road, (Earth Galleries), London. Sales Desks are also located at the BGS London Information Office, and at Murchison House, Edinburgh. The London Information Office maintains a reference collection of BGS publications including maps for consultation. Some BGS books and reports may also be obtained from HMSO Publications Centre or from HMSO bookshops and agents.

The Survey publishes an annual catalogue of maps, which lists published material and contains index maps for several of the BGS series.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG
☎ 0115-936 3100 Telex 378173 BGSKEY G
Fax 0115-936 3200

Murchison House, West Mains Road, Edinburgh, EH9 3LA
☎ 0131-667 1000 Telex 727343 SEISED G
Fax 0131-668 2683

London Information Office at the Natural History Museum, Earth Galleries, Exhibition Road, South Kensington, London SW7 2DE
☎ 0171-589 4090 Fax 0171-584 8270
☎ 0171-938 9056/57

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ 01392-78312 Fax 01392-437505

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 01232-666595 Fax 01232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Telex 849365 HYDROL G
Fax 01491-692345

Parent Body
Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Telex 444293 ENVRE G
Fax 01793-411501

PREFACE

Almost by definition, drought in drylands means that surface waters are scarce and groundwater is the principal, or only, source of supply. In severe drought, yields from these sources may decline markedly at a time when the demand for groundwater typically reaches a peak. The result may be falling numbers of viable water points and escalating social and economic costs. Set against longer term demographic and economic changes affecting demand and recharge patterns, the availability of perennial groundwater supplies cannot be assumed, as recent drought experience in southern Africa demonstrates.

The subject of drought in drylands has been extensively researched, particularly from food security, meteorological and sociological perspectives. However, relatively little attention has been focused on the impact of drought on groundwater resources. Drought management strategies reflect this fact. A typical strategy involves an emergency drilling programme in which rigs are imported, international expertise mobilised and large sums of money spent. The execution of these programmes is often poor, however. Wells are poorly sited, community participation is minimal and no preparation is made for the maintenance of new works. In addition, the response often comes too late, and it is not uncommon to find emergency drought relief wells being sunk after the rains have returned. Within a short space of time the stock of unsustainable water supply infrastructure is increased and funds have been diverted from longer-term programmes.

Against this background the UK Overseas Development Administration (ODA) has supported a project entitled 'Groundwater management in drought-prone areas of Africa' (project number R6233). A key contention of the project is that some wells, and some areas, are much more vulnerable to 'groundwater drought' than others, and that essentially predictable variations are rarely planned for or acted upon. One of the principal aims of the project is therefore to identify ways in which spatial and temporal information on the impact of drought on groundwater resources can be used to improve groundwater management. Ultimately the project will identify specific strategies that could be adopted or promoted by government and the donor community to (a) improve responses to 'groundwater drought' *within* drought episodes; and (b) improve longer term planning for groundwater drought *outside* drought episodes.

The project brings together institutions from four countries in an equal partnership. The countries (and institutions) involved are: Malawi (Ministry of Irrigation and Water Development (MIWD)); Ghana (Ghana Water and Sewerage Corporation (GWSC)); South Africa (Department of Water Affairs and Forestry (DWAF)), and the United Kingdom (the Hydrogeology Group of the British Geological Survey (BGS) and the Institute of Hydrology (IH)). Personnel from four of these institutions - MIWD, GWSC, BGS and IH - designed the project jointly in 1994. DWAF joined the network in 1996, with support from the British Development Division South Africa (BDDSA). Initially, the project will examine the experience of drought and groundwater drought in each of the African countries, documented in country-specific inception reports. Drawing from this common pool of experience and knowledge, the focus of the project will then shift towards the identification of management strategies. An international workshop will then be held in February 1997 to publicise and discuss findings with the government and donor community.

This document forms a small part of the overall project. The purpose of the report is to try to understand and model the behaviour of boreholes and wells under drought conditions. As time and resources were limited only simple models and scenarios have been used. Recommendations are given for future work that might give further insight into well/borehole behaviour under drought conditions.

This document is an output from a project funded by the ODA for the benefit of developing countries. The views expressed are not necessarily those of the ODA.

Contents

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

It has been suggested that variations in demand and yield are responsible for many groundwater sources failing during drought (MacDonald and Calow 1996). Demand for groundwater increases during drought as alternative sources dry up and the yield of individual wells and boreholes may decline as water-levels fall. These two factors could combine to precipitate well/borehole failure. To help test this hypothesis, a modelling exercise has been undertaken to simulate source and aquifer behaviour under drought conditions.

Initial modelling used the Jacob equation (Cooper and Jacob 1946). This illustrated several basic but important points: in a low transmissivity environment the cone that develops around a pumping well is deep and narrow; when the transmissivity (T) is high the cone of depression is expansive, but shallow. The storage coefficient (S) also affects the size and shape of the cone of depression: as S decreases the general depth and extent of the cone increases.

Further modelling used a more sophisticated analytical model that included well storage. This model was suggested by Papadopulos and Cooper (1967) and further developed for a semi-confined aquifer by Barker (1989). The Barker model was used to simulate drawdown conditions due to a pumping well and a borehole within a good basement aquifer (T = 10 m^2/d, S = 0.01) and a poor basement aquifer (T = 1 m^2/d, S = 0.01). Five scenarios were modelled using a combination of 'normal' and drought years (no recharge during the wet season) and constant demand and demand doubling 3-4 months into the dry season. The final scenario included groundwater recession.

The conclusions from the various scenarios were as follows:

- pumping drawdown in a borehole and adjacent aquifer is consistently larger than the equivalent pumping drawdown related to a larger diameter well;
- water levels in the vicinity of a borehole recover quickly relative to those around a well (this effect is much more pronounced in a low transmissivity environment);
- drawdown in a well/borehole is very sensitive to the demands put upon it; in a poor aquifer, the increasing demands can lead rapidly to well failure;
- in the moderate T environment (good basement aquifer), the fall in water level in wells and boreholes due to natural groundwater recession is larger than the drawdown induced by pumping;
- in the low T environment (poor basement aquifer), natural groundwater recession has little significance compared with the drawdown within the well/borehole due to an increase in demand for water;
- in all the pumping scenarios, drawdown at 100 m from the abstraction point was less than 1 m, at a distance of 1000 m drawdown was negligible.

The above simple modelling raises important issues about the design and operation of groundwater sources in drought prone areas. To accurately predict how a source will react to drought, the characteristics of the aquifer need to be known along with the amplitude of natural groundwater fluctuations. Since the water-levels in wells/boreholes are very sensitive to the demand put upon the source, rural water supply schemes should be designed to cope with the extra demand produced by endemic drought.

Under poor aquifer conditions, or where demand is high, the failure of groundwater sources during periods of drought may be due to *localised* dewatering of aquifers and not related to the *absolute availability* of

groundwater. This has significant implications for combating groundwater drought, both proactively (e.g.use of suitable well design, construction of more than one source for a village) and reactively (siting of emergency boreholes).

1. INTRODUCTION

In an earlier report (MacDonald and Calow 1996) it was suggested that the problems that arise in managing groundwater in drought prone areas are due primarily to variations in demand and yield from wells and boreholes. It was proposed that drought could precipitate well and borehole failure through both increases in demand for groundwater (as alternative sources dry up) and decreased yield of well/boreholes (as water levels fall). To help establish this framework a modelling exercise was undertaken to simulate source and aquifer behaviour during drought conditions. In particular, the exercise was used to investigate how the drawdown in pumping wells and boreholes compare with that in the adjacent and distant aquifer under a number of aquifer and pumping scenarios. This report contains the results of this basic modelling and draws preliminary conclusions on source behaviour with recommendations for future work.

2. BASIC THEORY

By combining Darcy's law with the theorem of mass conservation, groundwater flow equations are derived for an aquifer. Radial flow to a pumping borehole is governed by the following flow equation:

$$\frac{\delta^2 h}{\delta r^2} + \frac{1}{r}\frac{\delta h}{\delta r} = \frac{S}{T}\frac{\delta h}{\delta t} \qquad (1)$$

where r is the radial distance from the pumping well; h is the hydraulic head in the aquifer; t is the time since pumping began; and S and T are the derived aquifer properties, storage coefficient and transmissivity respectively. Subject to various boundary conditions a solution was found to this equation by Theis (1935) which revolutionised hydrogeology. The solution is written:

$$h_o - h(r,t) = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}du}{u} = \frac{Q}{4\pi T}W(u) \qquad (2)$$

where

$$u = \frac{r^2 S}{4Tt} \qquad (3)$$

h_o is the initial head in the aquifer; and $W(u)$ is known as the well function. Tables are widely available for calculating values of $W(u)$ and therefore the equation can be solved. If the pumping rate (Q) and the aquifer transmissivity (T) and storage coefficient (S) are known, then it is possible to calculate the drawdown (h_o - $h(r,t)$) at any distance from the well and at any time after pumping commences. The well function can be approximated by an expanded series:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - .... \qquad (4)$$

For drawdown measurements made sufficiently long after the start of pumping, the later terms become very small. The Theis equation can therefore be simplified:

$$s = h_o - h(r,t) = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2 S} \qquad (5)$$

where s denotes the drawdown at position r and time t. This equation is known as the *Jacob* equation (Cooper and Jacob 1946). The application of this equation is subject to certain assumptions about the aquifer (Kruseman and de Ridder 1990):

(1) the aquifer is confined
(2) the aquifer is of uniform thickness and infinite extent
(3) the aquifer is homogeneous and isotropic
(4) the piezometric surface is horizontal prior to the test
(5) the borehole penetrates the entire thickness of the aquifer
(6) water storage in the borehole is negligible
(7) the pumping rate is kept constant throughout the test.

3. CONES OF DEPRESSION

To illustrate the depth and lateral extent of the cones of depression that can develop around pumping boreholes and wells under a number of aquifer conditions during periods of no recharge, two mathematical models were used.

3.1 Jacob equation

A rough estimate of the shape of the drawdown curve and cone of depression can be obtained by using the Jacob equation. In this exercise three values of storage coefficient were used, 0.001, 0.01 and 0.1; two values of transmissivity, 1 and 10 m^2/d; and three pumping rates, 0.1, 0.3 and 1 l/s. The cones of depression that developed after a period of 100 days for selected combinations of variables are shown in Figures 1-3.

Changes in transmissivity have the largest effect on the shape of the cone of depression. When the transmissivity is low the cone of depression is deep and narrow, when the transmissivity is high the cone of depression is expansive but shallow (see Figure 1). Changes in the storage coefficient also affect the shape of the curve. As the storage available within the aquifer increases, so the size and general depth of the cone decreases as less of the aquifer needs to be dewatered to supply the borehole (Figure 2). The Jacob equation illustrates that the depth of the cone increases with increasing pumping rate (Figure 3). According to the Jacob equation the radius of the cone of depression would not change with increasing pumping rate. This however is not seen under natural conditions, but is due to the Jacob's approximation breaking down at large distances. (When u is large, >0.01, the later terms in the expanded series (equation 3) become significant).

3.2 Barker approximation

Use of the Jacob equation is limited because of its assumptions. Many groundwater sources in Africa are hand dug wells with diameters often greater than 1 metre and therefore the assumption that the volume of water stored in the well is negligible (assumption (6) above), is violated. A more sophisticated analytical model that copes with well storage has been suggested by Papadopulos and Cooper (1967) and further developed for a semi-confined aquifer by Barker (1989). The flow equations for the aquifer and aquitard are derived and solved by taking the Laplace transform with respect to time (see Barker (1989) for the appropriate mathematics, Figure 4 shows a schematic diagram of the conceptual model). The drawdowns are calculated by numerically inverting the Laplace transforms. The following conditions are assumed (see Figure 4):

(1) the aquifer is semi-confined
(2) the aquifer is of uniform thickness and infinite extent
(3) the aquifer is homogeneous and isotropic
(4) the aquitard is unconfined but the piezometric surface is horizontal prior to the test
(5) the borehole penetrates the entire thickness of the aquifer
(6) groundwater flows horizontally in the aquifer and vertically in the aquitard.

Unfortunately the model cannot represent unconfined flow or boundary effects.

The Barker model was used to simulate drawdown curves for a number of aquifer and pumping scenarios. The code was simplified to represent the Papadopulos and Cooper (1967) model, ie the aquifer is confined (or unconfined where the drawdown is negligible compared to the thickness of the aquifer and the storage coefficient represents specific yield rather than elastic storage). Drawdown curves were produced for two different sources: a borehole with diameter of 150 mm and a well with a diameter of 1.5 m. The cone of depression was calculated for aquifers of various properties, from a transmissivity of 0.1 to 100 m^2/d and storage coefficient of 10^{-4} to 0.1. The source was pumped for 12 hours a day at 0.1 l/s and the drawdown at the beginning and the end of pumping calculated for each day. To try and represent a long dry season of 7 months the source was pumped for a total of 220 days. The modelled cones of depression for two combinations of transmissivity and storage coefficient are shown in Figure 5.

As would be expected, the drawdown has a similar pattern to that produced by the Jacob equation (Equation 5): low transmissivity gives deeper, narrower cones; a decrease in storage coefficient makes the drawdown greater throughout the cone. It is possible to take the analysis slightly further with this model and compare the behaviour of boreholes and wells. Near to the source, pumping drawdown from the borehole is consistently larger than pumping drawdowns from the well. For a low transmissivity environment ($T = 1$ m^2/d; $S = 0.01$) this effect dies out away from the source until there is no discernable difference at about 10 m (see Figure 5a). After the pump has been switched off and the water levels in the source recover a different scenario is observed. Water levels in the vicinity of the borehole recover more quickly than in the well. This is due to a combination of the larger gradient that develops around the borehole and the smaller volume of water required to replenish the borehole volume. After 12 hours, the well still has not recovered to the level of the borehole.

A different scenario is observed in a high transmissivity environment ($T = 10$ m^2/d; $S = 0.01$). The difference in the cones of depression extends much further, to about 1 km (see Figure 5b), though in both the borehole and the well, the overall drawdown is small. Due to the high transmissivity, recovery happens quickly, therefore the well can recover to the same levels as the borehole within the 12 hours between pumping episodes. At larger distances, however, the well produces smaller drawdowns than the borehole, both in pumping and recovery.

In such environments with the pumping rates quoted, interference between sources and over exploitation of the aquifer are both unlikely to be problems. For both the well and borehole, at moderate and low transmissivity, the drawdown at 100 m was below 0.05 m and negligible at 1 km. Of all the other scenarios modelled, it was those with low storage that had the highest drawdowns at large distances. This is because a larger volume of the aquifer needs to be dewatered to yield the appropriate quantity of water when the storage per cubic metre is low.

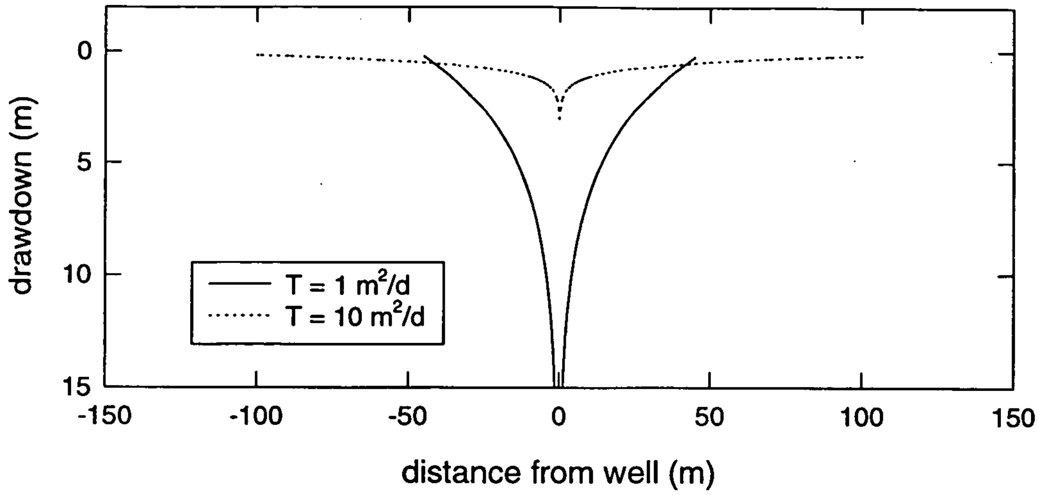


Figure 1 Cone of depression after 100 days, for S = 0.01, Q = 0.3 l/s and varying transmissivity (using Jacob's approximation).

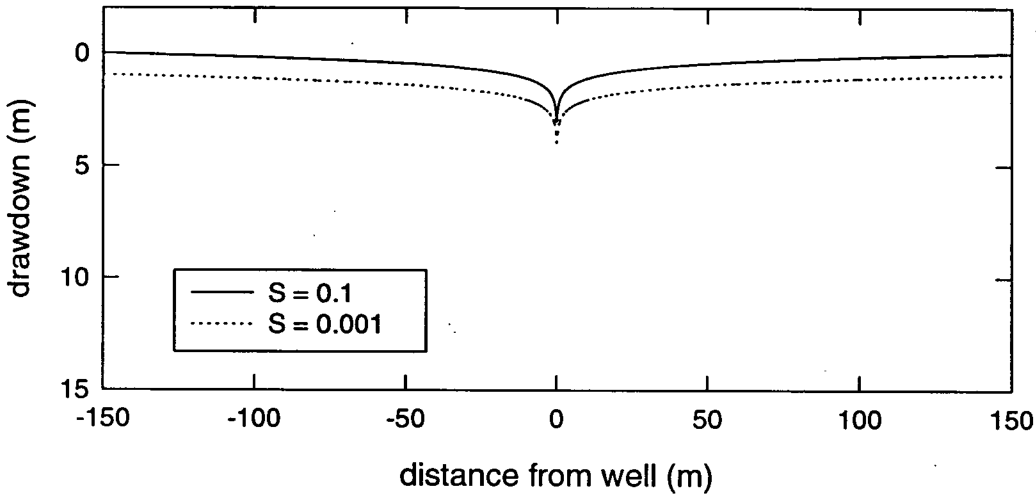


Figure 2 Cone of depression after 100 days for T = 1 m^2/d, Q = 0.3 l/s and varying storage coefficient (using Jacob's approximation).

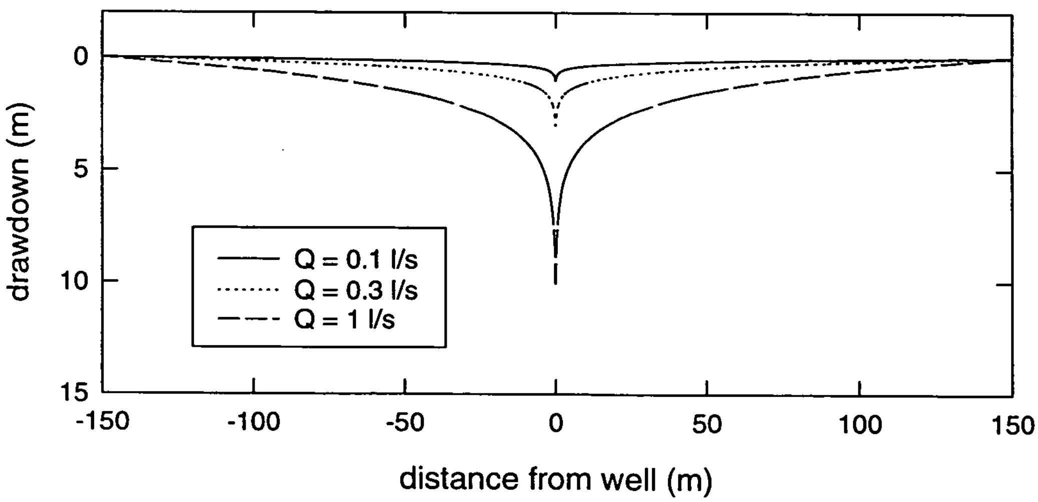


Figure 3 Cone of depression after 100 days for S = 0.01, T = 1 m^2/d and various pumping rate (using Jacob's approximation).

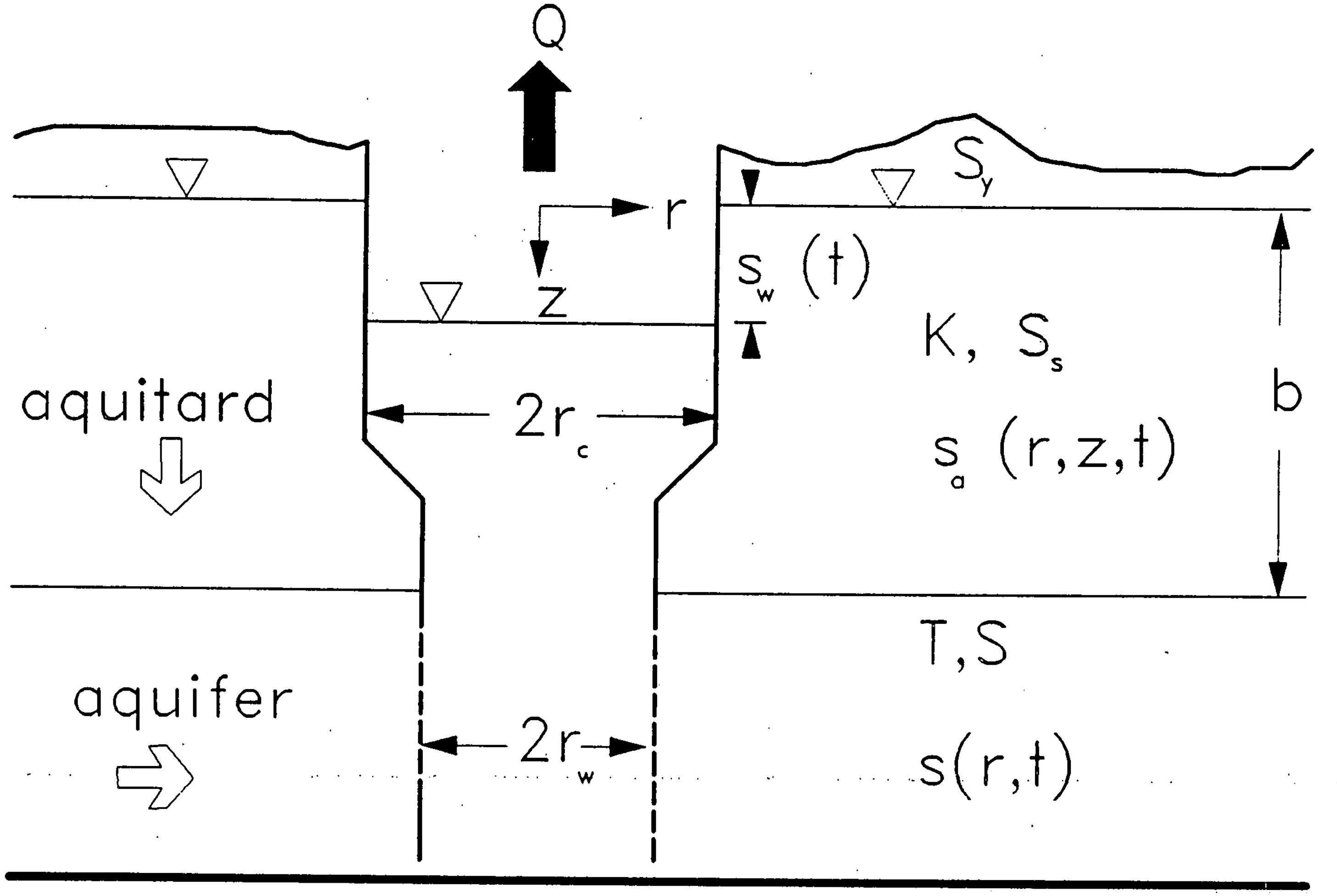


Figure 4 Schematic diagram of Barker (1989) model of a large-diameter well in a leaky aquifer.

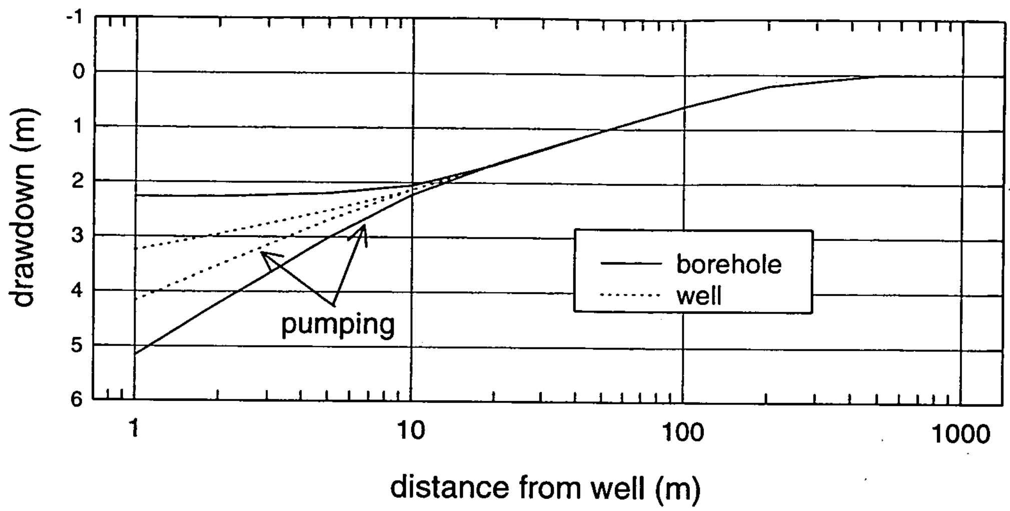


Figure 5a Drawdown in a borehole and well after 220 days of pumping at 0.1 l/s for 12 hours/day. Transmissivity is 1 m^2/d and storage coefficent 0.01. Drawdown is given at the end of pumping and after 12 hours recovery.

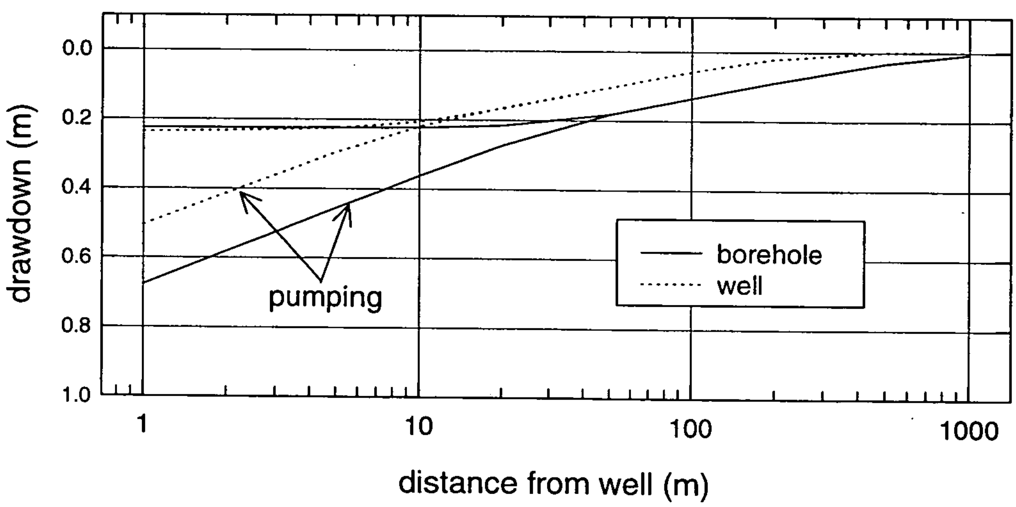


Figure 5b Drawdown in a borehole and well after 220 days of pumping at 0.1 l/s for 12 hours/day. Transmissivity is 10 m^2/d and storage coefficent 0.01. Drawdown is given at the end of pumping and after 12 hours recovery.

4. MODELLING SOURCE FAILURE

Part of the hypothesis put forward in MacDonald and Calow (1996) was that sources fail because the demand put upon them exceeds the capacity of the source to provide that water. The Barker model was used to give an estimation of water levels within both wells and boreholes as the dry season progressed and to predict when a source was likely to fail. The model used the two combinations of transmissivity and storage coefficient illustrated in Figure 5 to represent a good basement aquifer (T = 10 m^2/d, S = 0.01) and a poor basement aquifer (T = 1 m^2/d, S = 0.01), ie a thin or low permeability aquifer.

For the first example the aquifer properties were taken from a study in the weathered basement in the Upper regions of Ghana (Wardrop, 1980); transmissivity values of 7 - 30 m^2/d were measured, 10 m^2/d was chosen as a conservative estimate. The long term specific yield was quoted as 0.01. These figures agree with other studies (eg Wright and Burgess, 1992). Data for the second example was taken from a study in the Voltaian sediments of the Northern region of Ghana (SRDP, 1992). Data from short pumping tests were analysed. Transmissivity varied from 0.4 to 6 m^2/d with a geometric mean around 1 m^2/d. No storage data was available, but 0.01 is probably sufficient for a rough estimation.

The dry season was again assumed to be 220 days long. The aquifers were assumed to be fully recharged during the wet season. The model is limited by not accounting for decreasing transmissivity as the water levels fall. This means that in the model more water flows to the source than would happen in practice. In reality failure would happen sooner. No well loss has been added to the aquifer drawdowns. This should not give large errors since the pumping rates are small enough that non linear well losses would be negligible.

The failure criteria for a borehole was set at a water level of 20 m below ground level (bgl). The initial rest water level (at the end of the wet season) was taken as 5 mbgl. Therefore the drawdown (modelled using the Barker code) from end of wet season at which the borehole fails is 15 m. For the well, the failure criteria was set at a water level of 12 mbgl or a drawdown of 7 m. The rationale behind using these water levels stems from field experience. An average depth of borehole for basement aquifers was taken as 30 m. It is standard practice for the pump intake to be set at two thirds of the depth of the borehole, in this case 20 m or 15 m drawdown. The depth of hand dug wells is usually determined by the thickness of the weathered zone; an average thickness of 12 m is used here. A well fails when the water level falls below the base of the well or in this case when the drawdown is greater than 7 m.

Five scenarios are presented here for a combination of 'normal' and drought years, with demand remaining constant or doubling 3-4 months into the dry season. In scenario 5 natural groundwater recession is included. The drawdown curves from the five scenarios are shown in Figures 6-10.

Scenario 1: 'normal' year with no change in demand

In this situation the borehole/well was pumped at 0.1 l/s for 12 hours a day (giving a total of 4.32 m^3 per day). There was assumed to be no natural decay in the water levels over the period of pumping. The drawdowns in the borehole and well for both the good and poor aquifer are shown in Figure 6. The good aquifer has no difficulty in supplying 0.1 l/s, 12 hours a day throughout the dry season. Pumping water levels (PWL) are around 1 m below the original rest water level (ORWL) in the borehole and 0.7 m below ORWL in the well. Water levels recover to within a few centimetres below the previous day's rest water level before the next days pumping. The poor aquifer also copes with the level of abstraction, but by the end of the dry season the water levels are quite low. In the borehole water levels are at about 9 m below ORWL and in the well, 4.5 m below ORWL.

The drawdowns in the aquifers due to pumping are shown in Table 1. Water-levels were calculated at the end of pumping on day 220 at distances of 10, 100 and 1000 m from the source. The groundwater-levels after 12 hours recovery have been omitted for simplicity - at these distances recovery in the aquifer is negligible. Likewise no distinction has been made between the effect on the aquifer caused by wells or borehole (see section 3).

Table 1 **Drawdown in a good (T = 10 m²/d) and poor (T = 1 m²/d) aquifer after 220 days pumping in Scenario 1**

Distance from Source (m)	Drawdown in Good Aquifer (m)	Drawdown in Poor Aquifer (m)
10	0.36	2.2
100	0.14	0.59
1000	0.006	3.0×10^{-7}

For the good aquifer the drawdown at greater than 100 m from the well is less than 15% of the drawdown in the borehole; for the poorer aquifer the drawdown at 100 m is less than 1%. At a distance of 1000 m the pumping has no effect at all.

Scenario 2: 'normal' year with demand doubling 3-4 months into the dry season

This scenario reproduces the effect of alternative sources of water drying up into the dry season putting a much greater stress on the groundwater source. For a community of 250 people, 0.2 l/s for 12 hours a days would provide 35 l/capita/day. There was assumed to be no natural decay in the water levels over the period of pumping. Drawdowns in the borehole and well for both the good and poor aquifer are shown in Figure 7. As above, the borehole and well have no problems meeting this higher demand in the good aquifer. The conditions in the poor aquifer are more serious. According to the failure criteria set above, both the well and the borehole would have failed approximately 115 days into the dry season. If water levels were allowed to continue to fall past this cut off, they would have stabilized at about 8.75 m below ORWL in the well and 17 m below ORWL in the borehole. (Nb. If the model had allowed for a reduction in transmissivity with depth, the sources would have failed earlier). Therefore in the poorer aquifer neither source could cope with the increased abstraction. Table 2 shows the drawdowns in the aquifer at the end 220 days pumping.

Table 2 **Drawdown in a good (T = 10 m²/d) and poor (T = 1 m²/d) aquifer after 220 days pumping in Scenario 2**

Distance from Source (m)	Drawdown in Good Aquifer (m)	Drawdown in Poor Aquifer (m)
10	0.7	4.22
100	0.25	0.99
1000	0.007	3.0×10^{-7}

Scenario 3: drought year with no change in demand

In this scenario there is no recharge at the end of the dry season to enable water levels to recover and therefore there is a continuous fall in water levels over a period of 580 days. Again there was assumed to be no natural decay in the water levels over the period of pumping. The borehole/well were pumped at 0.1 l/s for 12 hours a days throughout the period (giving a total of 4.32 m^3 per day). The drawdowns in the borehole and well for both the good and poor aquifer are shown in Figure 8. The extended period of pumping has not significantly changed the modelled drawdowns in the well or borehole. Both the well and borehole cope with the demand with water levels stabilising at 5 m and 9 m respectively in the poor aquifer and approx. 0.75 and 1 m respectively in the good aquifer. Table 3 shows the drawdown in the aquifer at three distances from the source. Because of the highly compartmentalised nature of basement aquifers there is a high probability that the cone of depression may intersect a no-flow boundary, increasing the drawdown in the well or borehole.

Table 3 **Drawdown in a good (T = 10 m^2/d) and poor (T = 1 m^2/d) aquifer after 580 days pumping in Scenario 3**

Distance from Source (m)	Drawdown in Good Aquifer (m)	Drawdown in Poor Aquifer (m)
10	0.4	2.55
100	0.17	0.9
1000	0.023	9.0×10^{-3}

Scenario 4: drought year with an increase in demand 3-4 months into the dry season

This scenario has the same initial conditions as Scenario 2, pumping, however, continues for another year at the higher rate. Figure 9 shows the corresponding drawdowns in the sources. Again the good aquifer can cope with the higher abstraction and both the well and borehole, in the poorer aquifer, fail. Prolonged abstraction does not lead to much higher drawdowns, rather drawdowns are only slightly lower at the end of 580 days than they were at 220 days. In reality drawdown would be much worse as the model does not allow the aquifer transmissivity to decrease as water levels fall. Further, as explained in Scenario 3, actual drawdowns may be even greater due to the cone of depression intersecting aquifer boundaries.

However, ignoring the inaccuracies in the scale of the drawdown, the output from Scenario 4 illustrates the impact of prolonged pumping in aquifers of low transmissivity. The localised dewatering of the aquifer that occurs is shown in Figure 10. In the poor aquifer the water-levels in the vicinity of both the well and the borehole are above the failure criteria within a few metres of the source and the drawdown is less than 5 m within a distance of 10 m from the source. It is interesting to note that in the good aquifer there is no significant difference between the cones of depression created by the well or the borehole beyond 1 m; in the poor aquifer drawdown is different up to 10 m from the source.

Scenario 5: including natural groundwater recession

There has been little monitoring in Africa of the natural fluctuations in groundwater throughout the seasons. In one study of basement aquifers in Zimbabwe (Macdonald *et al* 1995), natural regional variations in water levels were found, in many cases, to be small compared to well drawdown associated with pumping.

A simple method has been used here to try to estimate natural fluctuations in the aquifers. Assuming our two aquifers (both with storage coefficient of 0.01) are undisturbed and in equilibrium (ie recharge each year is matched by natural discharge) and recharge is 30 mm/a, then the water levels would rise and fall by 3 m/a. Figure 11 shows the pumping water levels for both aquifers under Scenario 3 and 4 conditions, with a natural logarithmic decay superimposed (recovery water levels have been omitted for simplicity).

Superimposition of natural groundwater recession changes the source behaviour. For the poor aquifer the well and the borehole are disproportionately affected (Figure 11b). At the lower pumping rate of Scenario 3 the well fails before 220 days due to the regional recession of groundwater levels. Since the borehole is deeper the natural recession does not have such a large relative effect and the borehole remains operative. With the increase in demand the well fails at just over 90 days and the borehole at just over 100 days.

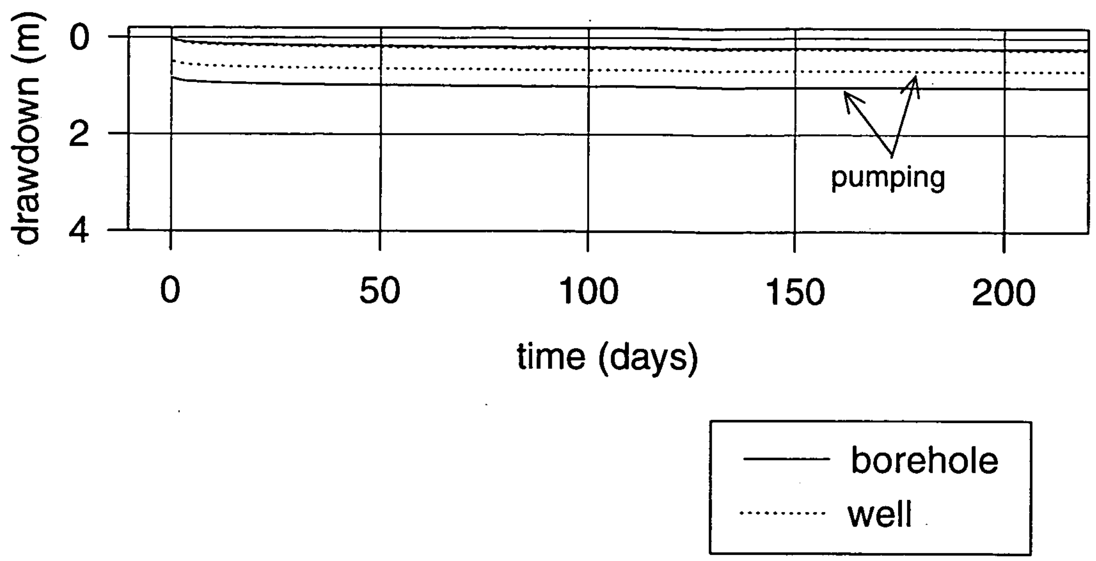
Natural recession also affects the good aquifer. The drawdowns shown in Figure 11a are largely a result of the natural recession rather than the pumping cone of depression. Since the borehole is deep there is no chance of failure. At the end of the second dry season, the well has a drawdown of over 4 m for the lower pumping rate, and nearly 6 m for the increased pumping rate. According to our criteria, the well is approaching failure.

Table 4 compares the drawdown within the aquifer as a result of pumping and that due to the natural recession. Within the good aquifer, drawdown is dominated by the natural recession. Within the poorer aquifer the pumping is the dominant control at 10 m from the borehole; at a distance of 100 m the natural recession constitutes 65% of the observed drawdown.

Table 4 **Drawdown in a good (T = 10 m^2/d) and poor (T = 1 m^2/d) aquifer after 580 days pumping in for Scenarios 4 and 5**

Distance from Source (m)	Drawdown in Good Aquifer (m)		Drawdown in Poor Aquifer (m)	
	no recession	with recession	no recession	with recession
10	0.78	4.01	5.0	8.23
100	0.33	3.56	1.7	4.9
1000	0.04	3.27	0.001	3.23

(a) good basement aquifer



(b) poor basement or clayey sedimentary aquifer

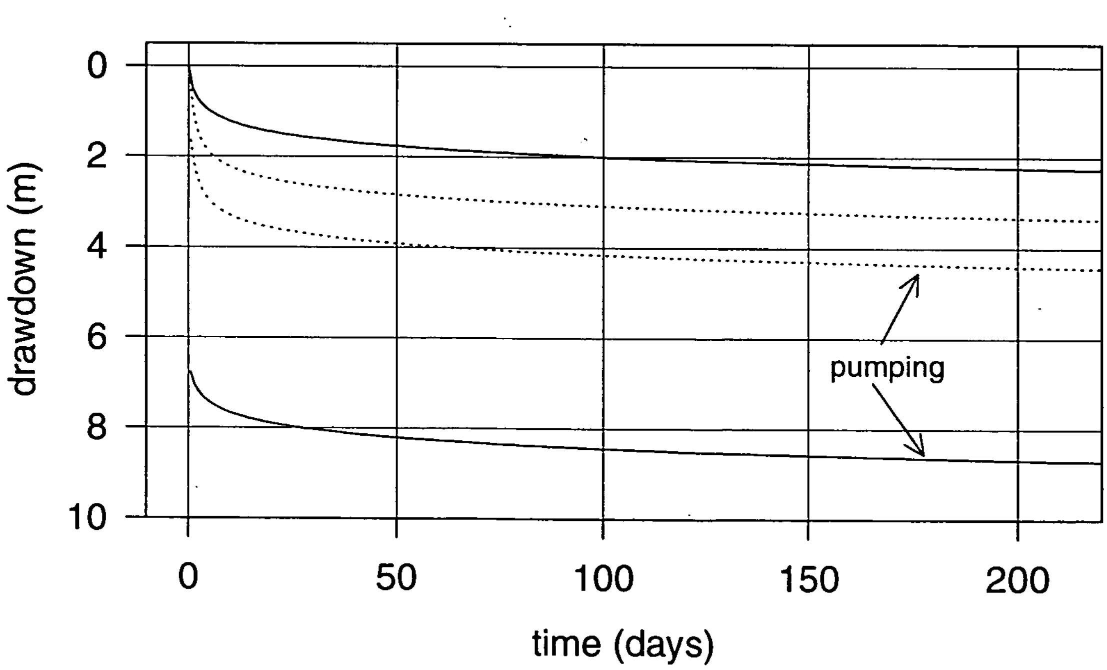
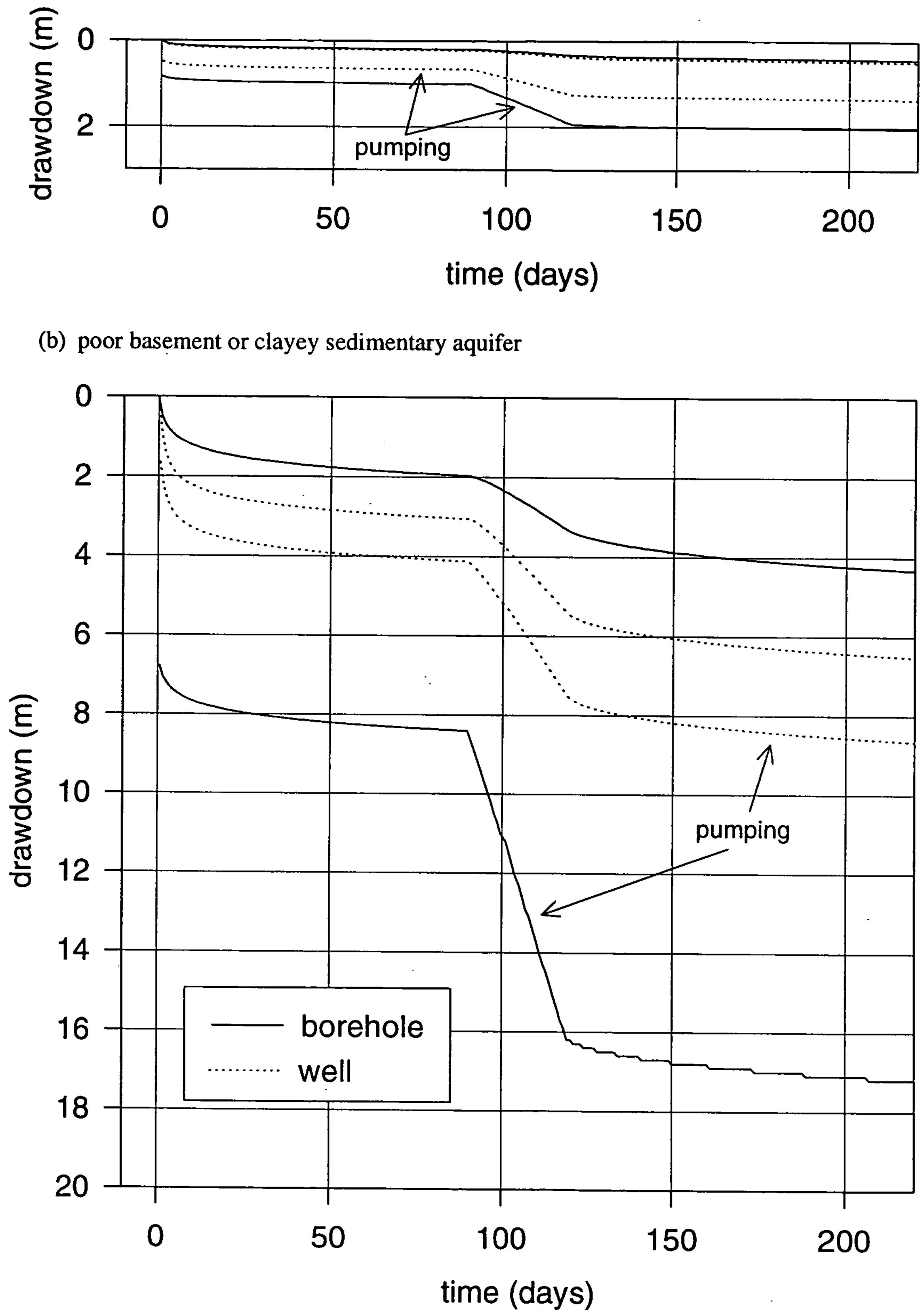


Figure 6 Water levels within borehole/wells in (a) a good aquifer and (b) a poor aquifer
Pumping at 0.1 l/s for 12 hours a day; both pumping and recovery water levels are given.

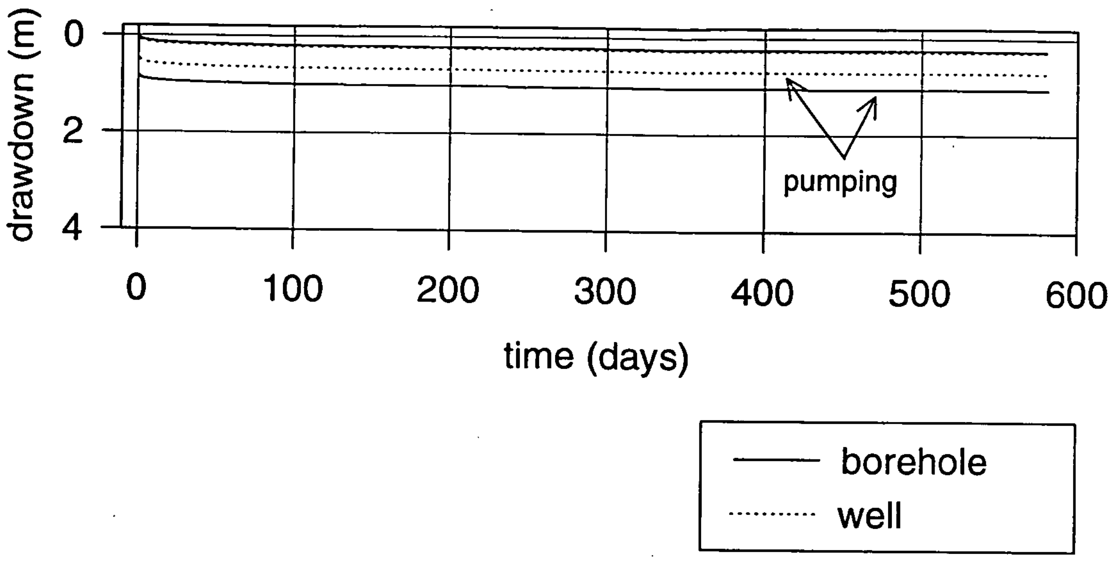
(a) good basement aquifer



(b) poor basement or clayey sedimentary aquifer

Figure 7 Water levels within borehole/wells in (a) a good aquifer and (b) a poor aquifer Pumping at 0.1 l/s for 12 hours a day for 90 days, increasing to 0.2 l/s from 120 days. Pumping and recovery levels are given for each day.

(a) good basement aquifer



(b) poor basement or clayey sedimentary aquifer

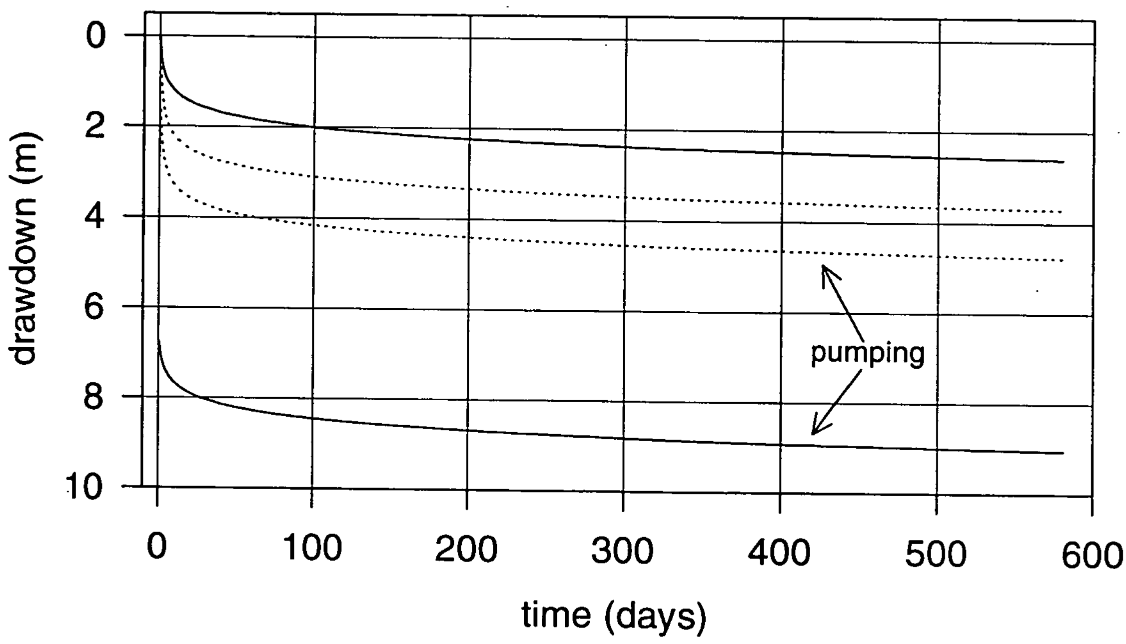
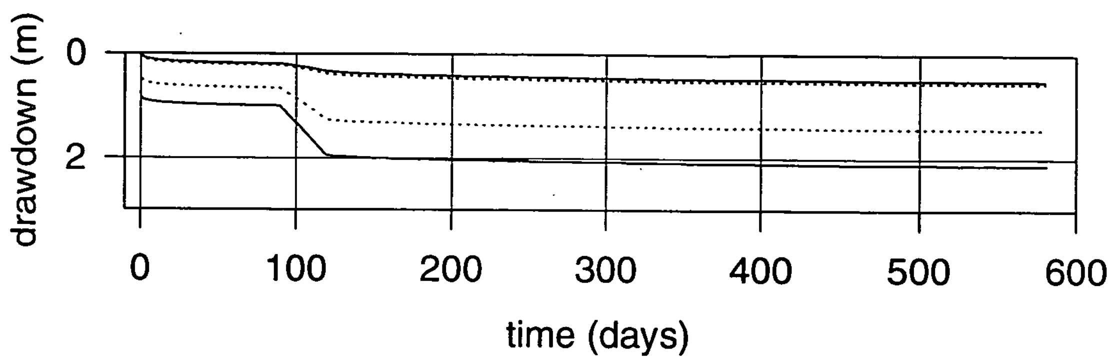


Figure 8 Water levels within borehole/wells in (a) a good aquifer and (b) a poor aquifer
Pumping at 0.1 l/s for 12 hours a day, water levels are for beginning and end of pumping.

(a) good basement aquifer



(b) poor basement or clayey sedimentary aquifer

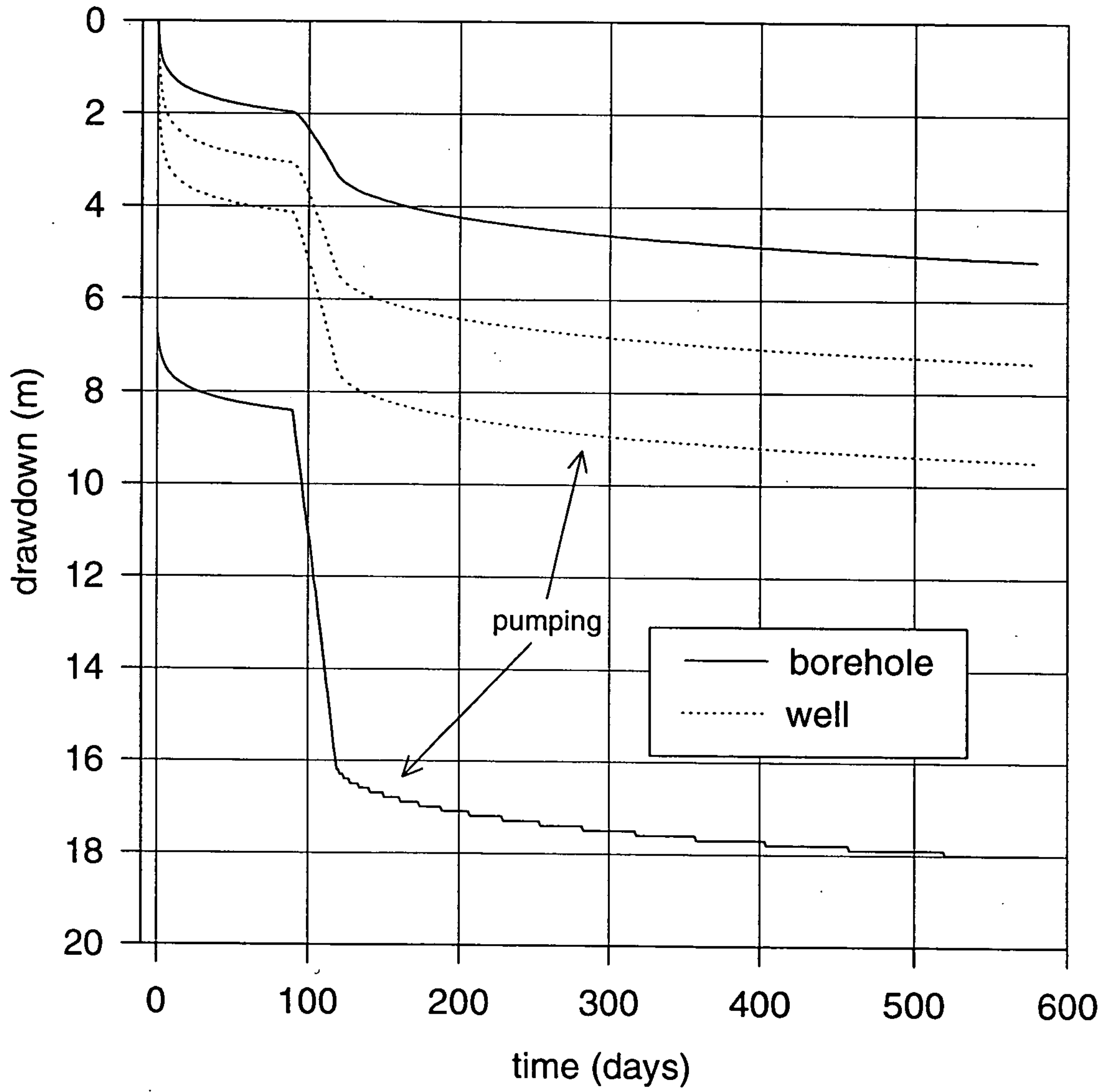
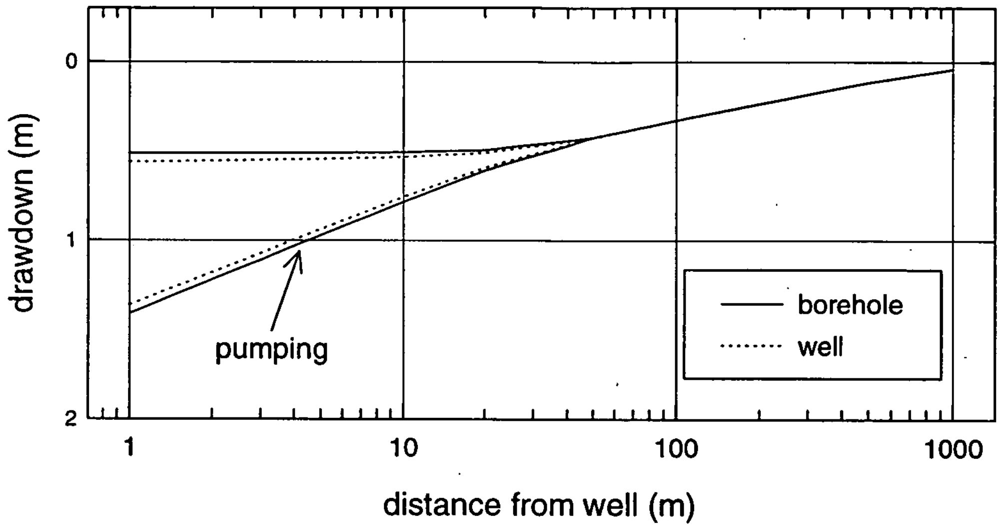


Figure 9 Water levels within borehole/wells in (a) a good aquifer and (b) a poor aquifer Pumping at 0.1 l/s for 12 hours a day for 90 days, increasing to 0.2 l/s from 120 to 580 days. Water-levels are shown for both pumping and recovery.

(a) a good basement aquifer.



(a) poor basement or clayey sedimentary aquifer.

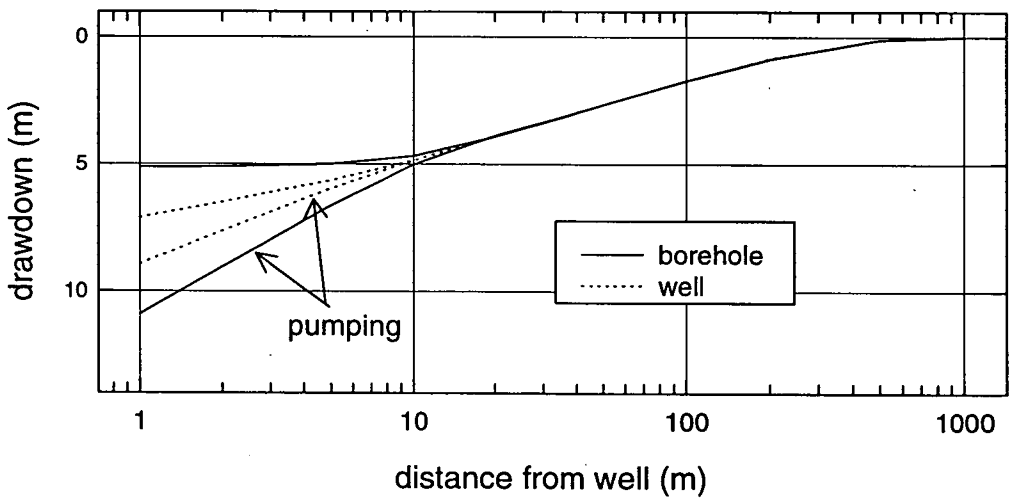


Figure 10 Cross-section showing water-levels in (a) a good and (b) a poor aquifer at then end of Scenario 4. Both the recovery and pumping water-levels are given for a well and borehole.

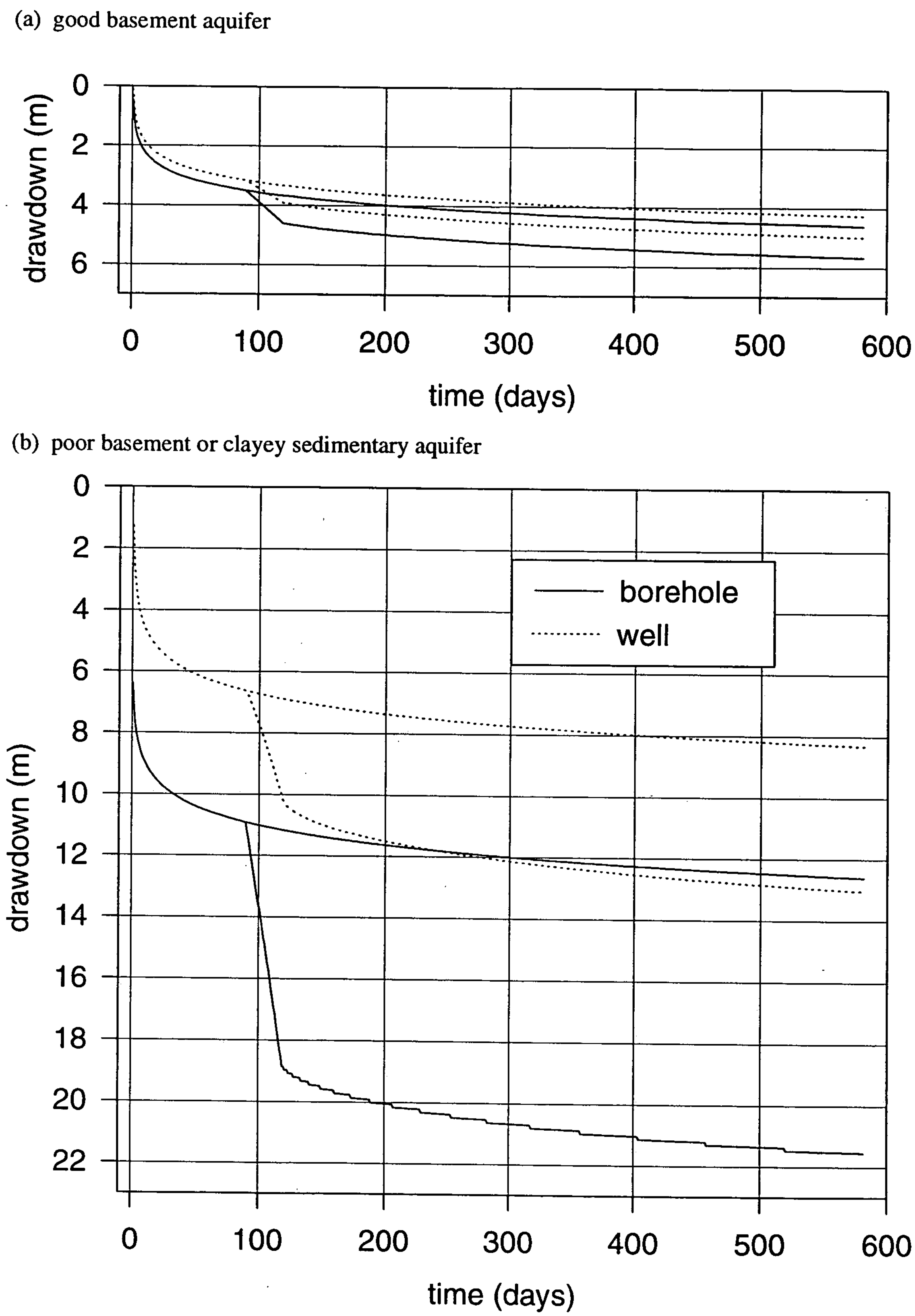


Figure 11 Water levels within borehole/wells in (a) a good aquifer and (b) a poor aquifer. Both scenario 3 (no change in pumping rate) and scenario 4 (increase after 90 days) are shown. Natural groundwater recession is included.

5. SUMMARY AND CONCLUSIONS

The modelling of simple scenarios has illustrated several important points:

- when transmissivity is low, the cone of depression that develops around a pumping well is deep and narrow; when the transmissivity is high the cone of depression is expansive, but shallow;
- as the storage coefficient within the aquifer increases, so the size and general depth of the cone of depression decreases;
- pumping drawdown in a borehole and adjacent aquifer is consistently larger than the equivalent pumping drawdown related to a well. The difference reduces away from the source - dependent on the transmissivity;
- water levels in the vicinity of a borehole recover quickly relative to those around a well. This is due to a combination of the higher gradient that develops around a borehole as a result of pumping and the larger storage volume of a well that needs to be replenished. This effect is much more pronounced in a low transmissivity aquifer;
- the storage coefficient has a significant affect on drawdowns at large distances from the source. Unless the storage coefficient is very low ($<<0.01$) drawdowns at a distance of 1000 metres are only a few centimetres;
- drawdown in a well/borehole is very sensitive to the demands put upon it; in a poor aquifer, the increasing demands can lead rapidly to well failure;
- in the moderate T environment (good basement aquifer), the fall in water levels in wells and boreholes due to natural groundwater recession is larger than the drawdown induced by pumping;
- in the low T environment (poor basement aquifer), natural groundwater recession has little significance compared with the drawdown within the borehole/well due to an increase in demand for water;
- in all the pumping scenarios, drawdown at 100 m from the source was less than 1 m; at a distance of 1000 m drawdown was negligible.

The observations presented above lead to more general conclusions related to the design and operation of groundwater sources, particularly in areas prone to drought:

i) it is very important to assess aquifer characteristics when deciding on the design of a groundwater source as this has a large affect on the subsequent drawdowns within the source itself;

ii) the natural fluctuations of water levels in the aquifer should be known to help estimate further declines during drought;

iii) the highest demands that the source can be put under need to be assessed as increasing demand in low permeability environments can quickly lead to the failure of the source. This again has implications for source design and operation. For example, the recovery of wells has been shown to be improved by drilling radials froma well (Herbert 1990). Additionally varying pumping regimes for the same daily abstraction can help to keep a source operative by reducing the maximum drawdown (Holt and Rushton 1984);

(iv) Under poor aquifer conditions the failure of groundwater sources during periods of drought may be due to localised dewatering of aquifers and not related to the absolute availability of groundwater. This has implications for both proactive measures (eg use of suitable well design, construction of more than one source for a village) and reactive measures (siting of emergency boreholes) to combat groundwater drought.

6. RECOMMENDATIONS FOR FUTURE WORK

The modelling in this study has been simple and illustrative rather than exhaustive. Within the time frame of the project there has not been the scope to use more sophisticated models. A series of recommendations are made here for work in future projects that would provide a more complete picture:

i) use the Barker approximation to model a further increase in demand at the failure of the rains;

ii) identify or develop more sophisticated models that will allow the following systems to be simulated

- layered aquifer with variable permeability and storage coefficients
- compartmentalised aquifers
- collector wells;

iii) investigate the effect of different pumping regimes - for the same daily quantity of water - on drawdown and source failure.

ACKNOWLEDGEMENTS

This project is supported by the British Overseas Development Administration Technology Development and Research Programme (R6233). Thanks are due to members of the BGS 'drought project' team - particularly N S Robins, the project manager - for their suggestions and criticisms of this document.

REFERENCES

Barker J A 1989. Programs to simulate and analyse pumping tests in large-diameter wells. British Geological Survey Technical Report WD/89/24.

Cooper H H and Jacob C E 1946. A generalised graphical method for evaluating formation constants and summarising well field history. *Trans. Amer. Geophys. Union.* **27**, 526-534

Herbert R 1990. Dug well vs collector well performance. British Geological Survey Technical Report WD/90/34.

Holt S and Rushton K R 1984. An investigation into the effect of different pumping regimes on drawdown in large diameter wells. *Journal des Sciences Hydrologiques*, **29**, 271-278.

Kruseman G P and de Ridder N A 1990. Analysis and evaluation of pumping test data. IRLI publication 47, The Netherlands.

Macdonald D M J, Thompson D M and Herbert R 1995. Sustainability of yield from wells and boreholes in crystalline basement aquifers. British Geological Survey Technical Report WC/95/50.

MacDonald A M and Calow R C 1996. The effect of drought on the availability of groundwater: towards an analytical framework. British Geological Survey Technical Report WD/96/3.

Papadopulos I S and Cooper H H 1967. Drawdown in a well of large diameter. *Water Resources Research* **3**, 241-244.

SRDP (1992) Water Supply Project: report on drilling and test pumping in the Northern region, Ghana. Internal report SRDP.

Theis C V 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Trans. Amer. Geophys. Union.* **16**, 519-524.

Wardrop 1980. Final hydrogeological report for drilling program, 1974-79. Ghana Upper region (CIDA) Water Supply Project.

Wright E P and Burgess W G (editors) 1992. *The hydrogeology of crystalline basement aquifers in Africa.* Geological Society Special Publication No 66, London.