BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

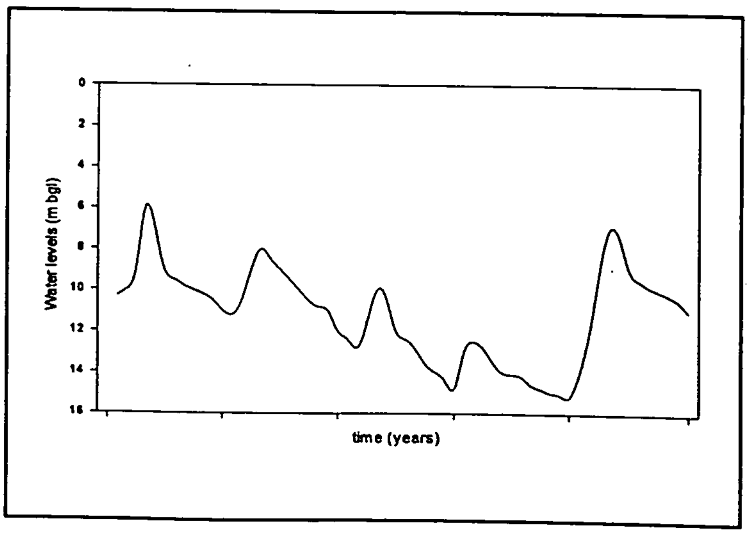
TECHNICAL REPORT WD/96/3
Hydrogeology Series

Technical Report WD/96/3

The effect of drought on the availability of groundwater: towards an analytical framework

A M MacDonald and R Calow

This report was prepared for
The Overseas Development Administration,
as part of Groundwater Management in Drought
Prone Areas of Africa, Project No. R6233



Bibliographic Reference

Author: MacDonald A M and Calow R
The effect of drought on the availability of groundwater: towards an analytical framework. British Geological Survey Technical Report No. WD/96/3.

Keyworth, Nottinghamshire

British Geological Survey 1996

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CLIENT	
OVERSEAS DEVELOPMENT ADMINISTRATION	CLIENT REPORT #
	BGS REPORT# WD/96/3
	CLIENT CONTRACT REF
	BGS PROJECT CODE E12HE009
	CLASSIFICATION OPEN

	SIGNATURE	DATE		SIGNATURE	DATE
PREPARED BY (Lead Author)	[signature]	16/2/96	CO-AUTHOR	R. Calow	16/2/96
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PEER REVIEWED BY	[signature]	16/2/96.	CO-AUTHOR		
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APPROVED BY (Project Director or senior staff)	N S Robins	15/2/96	CO-AUTHOR		
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Layout checked by	SHairhurst	15-2-96	CO-AUTHOR		

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CONTENTS

1. INTRODUCTION

This report forms part of an ODA funded study on groundwater management in drought prone areas. The study has case examples in northern Ghana, Malawi and South Africa. The purpose if this report is to lay down some preliminary ideas and thoughts about groundwater in drought prone areas and to suggest a framework for discussion. The majority of the ideas arose during a visit to the Northern and Upper regions of Ghana. It is hoped that the framework will be revised with further discussion and case studies.

2. GENERAL CONCEPTS OF GROUNDWATER IN DROUGHT PRONE AREAS

2.1 Drought definitions and concepts

The subject of drought in drylands has been extensively researched, particularly from meteorological, sociological, and agricultural perspectives. Typically, however, the work of natural and social scientists remains separate, with drought definitions varying accordingly. The lack of a universally accepted definition, and the inherent difficulties associated with divorcing causes from impacts creates some confusion and analytical difficulty. (see Box 1).

Box 1 Definitions of drought

From a *meteorological* standpoint, drought exists when rainfall is abnormally low, i.e. less than a critical precipitation that defines initiation of drought (Bruwer 1990, Solanes 1986). Area specific definitions abound. For example, in South Africa, Chavula (1994) defines drought as occurring when rainfall in any particular period is 70% of normal, becoming severe when this occurs over two or more consecutive seasons.

In *hydrological* terms, drought has been defined as occurring when actual water supply falls below the minimum required for 'normal' operations, reflecting a deficit in the water balance (Bruwer 1990, Solanes 1986). A similar definition, encompassing supply in broad terms in relation to demand, is offered by Hazelton *et al* (1994), when they state that drought occurs when there is a deficit in water, including surface and sub-surface water runoff and storage, as well as rainfall. This brings us to the rather 'catch-all' definition of drought, of arising when demand exceeds supply.

Agricultural drought exists when soil moisture is depleted to the extent that crop and pasture yields are considerably reduced (Bruwer, 1990; Solanes, 1986).

Drought is therefore a relative concept, defined in terms of a deviation from the norm. In defining drought, sufficient data must exist to help describe the normal conditions of the system

What seems clear is that defining drought is a side issue. The important point is that drought is a relative, not an absolute concept, and that its impact is highly variable over time and space. It implies some significant decrease in normal rainfall which is translated into adverse impacts on human systems. How (or whether) the effect of rainfall failure is translated into adverse impacts will depend on the severity and duration of the failure, the sensitivity of the physical system to changes in rainfall and the vulnerability of social and economic systems. Box 2 draws together some key concepts.

Box 2 Risk, sensitivity and vulnerability to drought: introducing some key concepts

Natural hazards, including drought, have traditionally been represented as the product of a natural system (the physical environment) and a set of human activities and responses. This approach has focused on the immediate effects of and responses to hazards, emphasising the short time horizons over which events occur (drought as a 'short term shock'). In more recent years, attention has focused on notions of vulnerability (to adverse consequences). These notions attempt to deconstruct, or desegregate, the social and economic space of impacts, to answer more fundamental questions of why certain areas and groups of people are disproportionately affected by drought. Time horizons are necessarily longer, as changes in vulnerability are likely to be the outcome of long term social and economic change.

Key concepts include:

Risk: the probability of occurrence of a hazardous event, such as failure of the rains, of specified magnitude and duration.

Sensitivity: a measure of the extent of impacts for a given hazardous event. Resilient, less vulnerable natural and human systems will be less sensitive to hazards. Generally speaking, the buffering capacity of aquifers to variations in supply and demand implies that groundwater systems, and the activities they help support, are inherently less sensitive to rainfall failures than surface systems.

Vulnerability: a measure of the underlying factors that influence exposure to the hazardous event and predisposition to adverse impacts, for a given population or region. The term refers to adverse consequences (e.g. loss of life; disease; migration; economic loss) rather than the hazardous event itself (failure of the rains) and, as such, "...encompasses the human ecology of resource use, economic entitlement and political economy" (Downing, 1993).

Targeting responses and resources before and during drought episodes depends on knowing who is most vulnerable. In addition, the planning of responses requires knowledge of the ways in which a hazardous event is translated into an adverse impact. In the case of drought and its impact on groundwater (and the human systems it helps to sustain), the chain of events may be far from clear. Failure of the rains may not have an immediate impact on groundwater resources because of the natural buffering capacity of groundwater systems, and the lag effect that results. The nature of the impact resulting from this lagged physical effect may also vary greatly over space and time, depending on the physical, social and economic factors that determine vulnerability (see above). The range of adverse consequences is understandably wide. Examples could include the migration of people away from water scarce areas and the abandonment of lands and livelihoods; health problems if people are forced to use poor quality sources such as dugouts in dry river beds; and death of cattle and livestock as competition for the few remaining water sources increases.

Attitudes and responses to drought in developing countries are often characterised by a pre-occupation with food. This is understandable: over the last two decades or so, international humanitarian relief for drought affected areas of Africa has steadily increased and, although such countries have suffered from recurrent drought for centuries, it is only recently that drought has been associated with widespread food insecurity (Buchanan-Smith, 1992).

Over recent years, understanding of the factors contributing to food insecurity and famine has increased (see Table 1). The African droughts of the 1980s and 1990s led to intensive research on methods to predict and monitor famine, and understanding of the economic, social and political dimensions of drought increased rapidly, with a shift in emphasis to the (longer term) protection of livelihoods as well as lives. Nevertheless, most drought interventions today are still characterised by:

1) A short term approach to the problem. Droughts are managed as one-off events, often by means of emergency programmes which are wound down once the emergency is perceived to be over

2) The assumption that basic water needs are met, and that it is access to and availability of food that are the principal concerns. Recent experience in southern and eastern Africa (e.g. Zimbabwe in 1989; Malawi in 1992-93) indicates that water availability (usually groundwater availability) cannot be taken for granted.

Given the fact that the availability of water must be a precondition for any effective food/livelihood related intervention, its neglect in the literature seems striking by its absence.

Table 1 **Evolution of thinking on drought: perceived causes, impacts and policy responses. The thinking behind this particular study is outlined below the dotted line**

Perceived cause of drought	*Perceived Impact of rain failure*	*Policy response*
Failure of the rains	Failure of rainfed crops impacting on supply of food. Not enough food to meet consumption needs.	Food aid - protection of lives
Failure of the rains; increase in demand	Failure of rainfed crops affects incomes, and thus access and entitlement to food.	Food aid; income transfers; (food for work programmes; food stamps); targeting (lactating mothers and babies). Protection of lives and livelihoods; reactive emergency drilling programmes
....	....	....
Failure of the rains; increase in demand; availability of water.	Availability of, and access to, food and *water resources*	As above, plus: drought proofing resource management

2.2 The role of groundwater in coping with drought

2.2.1 *The importance of groundwater resources*

Groundwater is often thought of as a mysterious resource, defying logic and science. This attitude has led to it being managed inappropriately in many parts of the world and therefore not gaining maximum benefit. Before considering the role groundwater can play in coping with drought it is important to clarify the "mysterious" nature of the resource and identify the properties of groundwater that make it such a valuable resource. Four particular aspects are outlined below.

1) Groundwater does not exclusively rely on seasonal rainfall. Aquifers can store much larger quantities of water than their annual recharge, therefore, if rainfall is particularly low over a short period (e.g. one or two years) there are usually sufficient reserves to provide a reliable perennial supply. This effect is here called the 'buffering capability' of groundwater (Figure 1). Unlike surface water, groundwater does not suffer evapotranspiration losses, therefore there is little natural depletion of the resource. The time lag, and the magnitude of the eventual impact on groundwater resources, will vary with the severity and duration of the 'surface' drought, the physical (hydrogeological) environment.

2) Groundwater resources can be accessed from many locations allowing the supply to be provided at the point of need, for example in the centre of a village. There is no need for large and expensive piped systems to transfer the water - the aquifer provides a natural reticulation system.

3) Technology for accessing groundwater can be quite simple and doesn't require large engineering structures. Hand dug wells and the drilling of boreholes can be quite easily managed by capable NGO's and regional government and can be constructed quickly at reasonable cost.

4) Groundwater is generally of good and reliable quality even during prolonged drought. Water stored in reservoirs, ponds and rivers is easily contaminated especially in times of shortage when quantity reduces and the dilution capacity reduces. Groundwater is less vulnerable as it cannot be directly contaminated, but only via seepage through the unsaturated zone (contamination of the *source* can occur through badly constructed wells/boreholes).

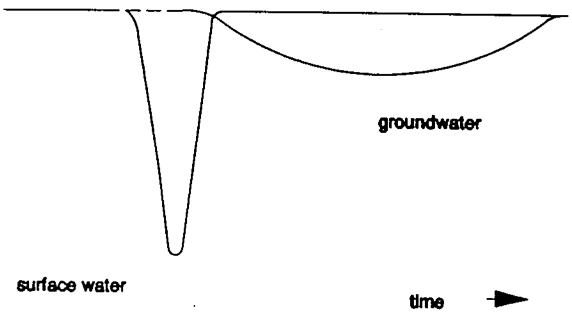

Figure 1 The different response times of surface water and groundwater to drought.

2.2.2 *The limitations of groundwater*

Because of its many advantages, groundwater might be (and in some cases, is) proclaimed as the solution to water shortages in drought prone areas. However, there are several aspects of groundwater resources that limit effectiveness in coping with drought.

1) The first is obvious: some areas do not posses usable groundwater resources. The groundwater may not be of adequate quality for consumption, e.g. having a high concentration of total dissolved solids (TDS), or fluoride, or arsenic. In other locations, groundwater may not be present in sufficient quantities to sustain exploitation. This could occur in geological formations with negligable primary porosity or fractures in which to store groundwater.

2) Even if groundwater is abundantly present within an aquifer it can only be accessed at discrete points via wells or boreholes. Therefore the amount of water that is supplied is a function not only of the volume of available resource but also of the number of access points to that resource. This problem does not arise with surface water where water can be accessed at any point within the body of the resource. In addition groundwater cannot be moved or engineered easily and generlly reguires energy to pump it to the surface.

3) Basement rocks underlie the majority of drought prone areas (Wright and Burgess 1992). The low permeability of these rocks (< 1 m/d) ensures that the flow of water towards wells and boreholes is restricted and the resource although present cannot be accessed at the required demand.

4) Groundwater also recovers slowly. The delay between changes of recharge and falling water levels is one of the primary benefits of using groundwater in drought prone areas (see above). However, this delay also has a negative impact - water-levels are affected over a long period (see Figure 1). Therefore the resource should be managed carefully long after the surface water drought has ended.

Before employing groundwater as a solution to the water needs of areas prone to drought, it is essential to understand the nature of the resource and the aspects particular to the aquifer in question. Too often the limitations of groundwater are ignored and a water supply system or drought relief programme is planned without due attention to the aquifer system. The success of the resulting programme will rely entirely on luck and good fortune, hoping to hit a sustainable groundwater supply. Only when the limitations as well as the benefits are understood can groundwater be managed to its maximum potential.

3. A FRAMEWORK FOR STUDYING DROUGHT AND GROUNDWATER

3.1 Introduction

In drought-prone areas the management of groundwater presents some interesting problems, subtly different to the usual set of problems that need to be considered. A key contention of this project is that it is not the *resource* that is at risk during times of drought, but rather *individual sources that become stressed* and cannot deliver the supply of water required to meet demand. Long term over-exploitation of the resource is therefore not considered in any detail in this study[1].

The behaviour of groundwater sources in drought-prone areas has to be understood before effective groundwater management strategies can be devised. During drought episodes, groundwater may be the only source of supply. Effective management, however defined, must therefore ensure that access to water is maintained to protect lives and livelihoods (for example, ensuring that basic domestic needs can be met without sacrificing other productive activities to the quest for water), and to ensure that other drought interventions are effective (most depend on people staying put). At its highest level, effective management, ensuring "access" to water, must logically ensure that:

- groundwater is present within wells (this is essentially a function of underlying trends in demand and supply)

- wells are operational, i.e. water which is within the well can be brought to the surface (this is essentially a maintenance issue, as it depends on wells being in good working order).

These considerations are not mutually exclusive. When sources become stressed, perhaps because others in the neighbourhood have dried up, the risk of breakdown increases. Likewise, individual sources may be more likely to dry up when surrounding sources have broken down. In this way, the two may reinforce each other.

A framework is suggested here for studying groundwater and drought. First the ability of a borehole or well to yield water during drought periods is described, then the changing patterns of demand for groundwater. The two are then linked into one framework.

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[1]Over-exploitation is a large topic and covered in detail in other reports (e.g. Adams and MacDonald 1995, Simmers *et al* 1992)

3.2 The yield of boreholes/wells during drought

The water table within an aquifer moves up and down in response to rainfall. This movement can be measured and gives rise to a hydrograph, a curve whose shape is a function of recharge, abstraction and the properties of the aquifer (Figure 2). During the wet season, the aquifer is recharged and water levels are high; in the dry season there is no recharge and the water-levels fall.

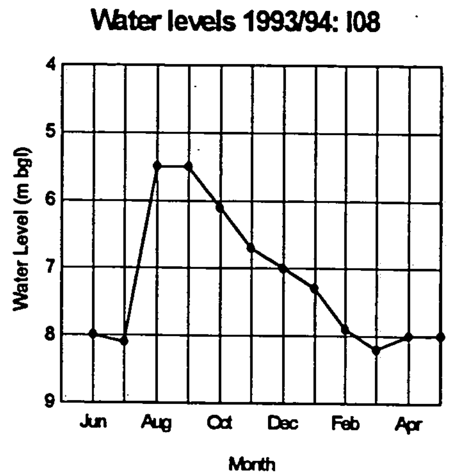

Figure 2 Hydrograph for a borehole in Northern Ghana. Water levels rise during the wet season and fall throughout the dry season.

As a consequence of the fluctuations in water levels the quantity of water available from a shallow well/borehole varies throughout the season. When the water level is higher than usual, the saturated thickness of the aquifer and water can flow into the well/borehole at a faster rate. This can be illustrated simply using Darcy's law:

$$Q=kA\frac{dh}{dx}$$

where Q is the flow into the borehole; A the cross sectional area of the borehole/well screen; k the hydraulic conductivity; and dh/dx the hydraulic gradient within the aquifer. Higher water levels increase the saturated cross-sectional area of the screen, A, and therefore increase the volumetric flow rate into the well borehole.

In the same manner, when water levels within the aquifer fall during the dry season the saturated cross-sectional area of the borehole/well falls and the yield of the borehole will decline. Therefore as the water levels rise and fall throughout the year, so the yield of the well/borehole increases and decreases. The amplitude of the variations in yield in response to changing water-levels depends both on the geology of the aquifer and also the design of the well/borehole.

During periods of drought, recharge is lower than normal and therefore water levels do not fully recover during the wet season (Figure 3). At the onset of the dry season water-levels within the aquifer are low and therefore continue to decline to levels lower than would be expected during a 'normal' year. Therefore there is a corresponding decrease in yield from the borehole/well, again the amplitude of these variations depends both on the geology and the design of the borehole/well (see Box 4).

In low permeability aquifers, yield can also change throughout the day. Early in the morning, water levels within the borehole/well are generally similar to the levels within the aquifer. Throughout the day however, water is often abstracted at a higher rate than groundwater flows into the borehole/well, therefore the water levels fall and the yield declines. During the night, when the borehole/well is not used the water levels generally recover.

Longer term processes can also affect the "supply" of groundwater. If there is a long term shift in the actual physical equilibrium, then the yield of boreholes/wells can be affected. For example, recharge to the aquifer can be affected by changes in the climate or land use.

The yield of individual wells and boreholes can therefore be affected over different time scales. Yields can change (1) throughout the day; (2) seasonally; (3) over a period of several years; and (4) long term. How the yields change depends on the physical system, the recharge and the permeability and storage capacity of the aquifer.

Box 4 Factors affecting the yield of boreholes/wells

Resource factors:

Recharge: low rainfall (e.g. during the dry season or periods of drought) limits the amount of recharge to the aquifer and results in low water levels within the aquifer and possibly low yields. Recharge is also affected by the evapotranspiration, soil type and land use of the area

Aquifer properties: if an aquifer has low permeability, groundwater cannot flow quickly through the aquifer to a borehole/well and therefore the yield is low. Also, if the storage capacity of an aquifer is low, water levels can quickly decline, making the aquifer much more susceptible to changes in discharge and recharge.

Source factors:

Type and design of borehole/well: the depth, diameter, and lining of the borehole/well can all affect the yield. Large diameter wells allow large quantities of groundwater to be stored and are good for low yielding areas; collector wells can be used to increase the yield of large diameter wells be drilling horizontally; boreholes can be useful in tapping deep fracture zones.

Siting of borehole/well: the properties of basement aquifers can vary greatly between different sites. Careful selection of the location of a borehole/well can significantly improve the yield.

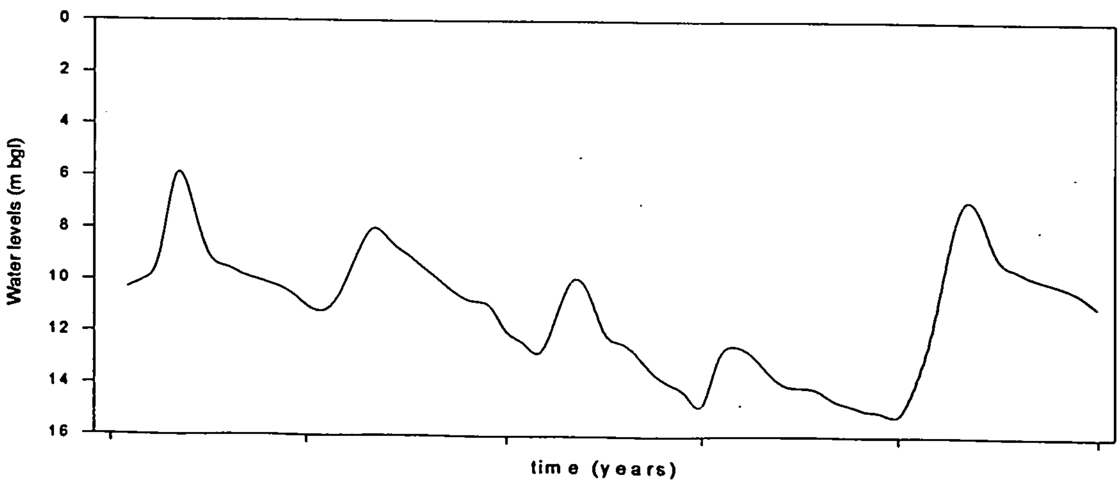

Figure 3 Water levels fluctuations in a borehole over a drought period.

3.3 Demand for water

While the discussion above sheds light on the availability of water under different conditions on its own it does not describe drought. If no one wants or needs the water, then there is no drought. Therefore the other side of the drought "equation" has to be introduced - demand.

Demand for water depends on a wide range of factors. Some of these are sector-specific (internal), whilst others are related to the wider demographic and economic environment in which human activities occur. All are likely to vary over time.

Internal factors (to sector):

- characteristics of the particular resource and supply
- quality and cost of the service
- water rights, water law etc

External factors (to sector):

- current and future population level
- current consumption level
- level and nature of economic activity
- household income
- opportunities for water use
- cultural factors
- wider social and institutional context
- availability of substitutes (money; technical expertise etc)
- season, weather etc

Figure 4 illustrates how both short term and longer term changes in demand for groundwater can affect water availability and the source stress. Any change will involve either changes in per capita use and/or changes in the number of users (and uses).

i) Short term seasonal fluctuations

Demand may fluctuate seasonally because of changes in:

- number of uses to which water is put (e.g. dry season mud block construction; dry season irrigation)

- availability of alternative (e.g. surface) sources

- seasonal migration patterns (e.g. in response to work opportunities)

- water required to meet basic needs

An a priori conclusion is that dry season demand will exceed wet season demand as alternative surface water sources dry up or deteriorate, the number of uses to which water is put increases.

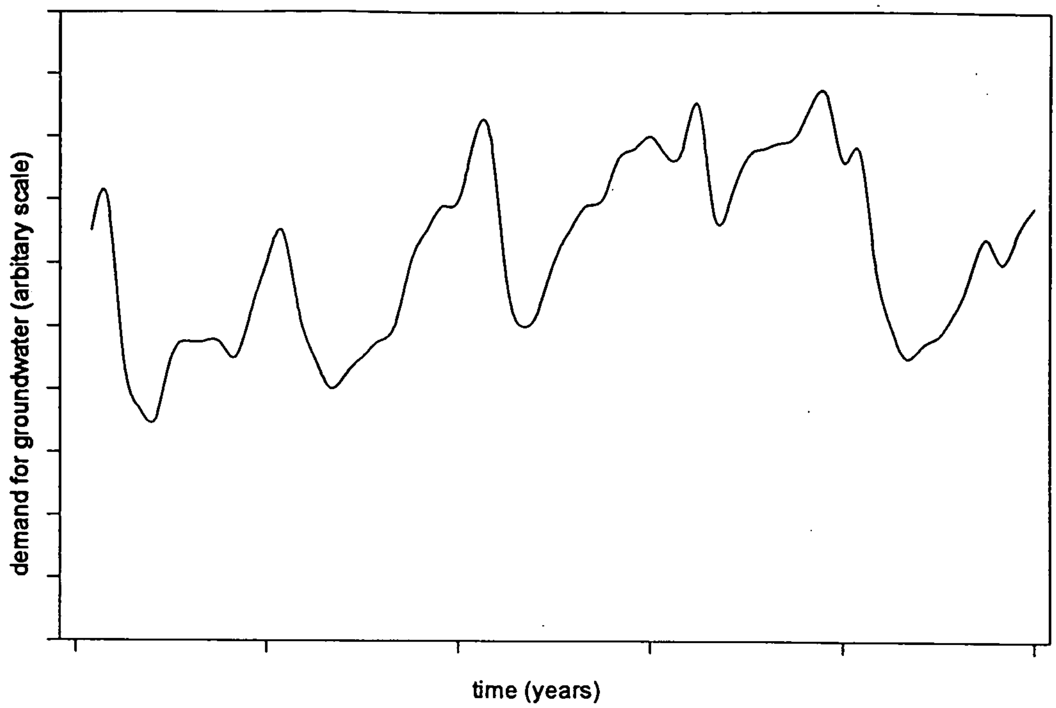

Figure 4 Fluctuations in demand for groundwater in a rural African environment.

During drought years when the rainfall is low, demand on individual groundwater sources can increase both during the wet and dry seasons. This is partly due to the lack of surface water resources and also the increasing unreliability of boreholes/wells because of the extreme usage.

ii) Longer term trends

Over the longer term, more widespread changes in economic and demographic conditions may affect water demands. These may include:

- population growth and migration patterns
- economic development (which typically raises incomes and increases the range of uses to which water is put)
- policy decisions (for example those relating to food self sufficiency and the promotion of irrigation)

An a priori conclusion is that water demands, especially when starting from an extremely low level, are likely to increase over time. This is illustrated in Figure 4 as an upward trend in the seasonally fluctuating demand curve. This upward trend may serve to exacerbate the effects of shorter-term failures on the supply side.

3.4 Yield, demand and drought

Groundwater drought is an intricate combination of the yield from individual sources and the demand put upon these sources. Figure 5 combines the demand and yield curves from above to illustrate groundwater availability and groundwater demand.

It is immediately apparent that demand for groundwater is highest when boreholes/wells are least able to provide water. Towards the end of the dry season most alternative supplies of water have disappeared and communities are dependent on groundwater. Water levels within the aquifer, however, are naturally at their lowest at this time and therefore yield is low. This effect is exacerbated during years of drought, when alternative supplies are available for less of the year and extra pressures of migration lead to escalating demand and the water levels within the aquifer are severely depressed.

If a borehole/well can only just meet the demand for groundwater under a normal year, during a drought year demand will not be met (see Box 4). The increasing stress put on the borehole/well can

Box 5 Example of declining yields

In northern Ghana, a demand of 10 m³/d per source was calculated for the dry season water requirements of communities reliant on boreholes/wells (MacIvor 1993).

Take a simple hypothetical example of a borehole which penetrates 6 m below the water table in an the aquifer with hydraulic conductivity of 0.11 m/d. A yield of 0.3 l/s is available without the borehole drying up.

If this could be pumped constantly for 10 hours a day, 10.8 m³ groundwater would be available from the borehole and water demands can be met.

If the regional water level in the aquifer fell by 2 m then only 0.13 l/s could be gained from the borehole without it drying up. This corresponds to 4.6 m³/d for 10 hours constant pumping. Therefore even without allowing for a further increase in demand due to drought, the source is stressed beyond its capacity.

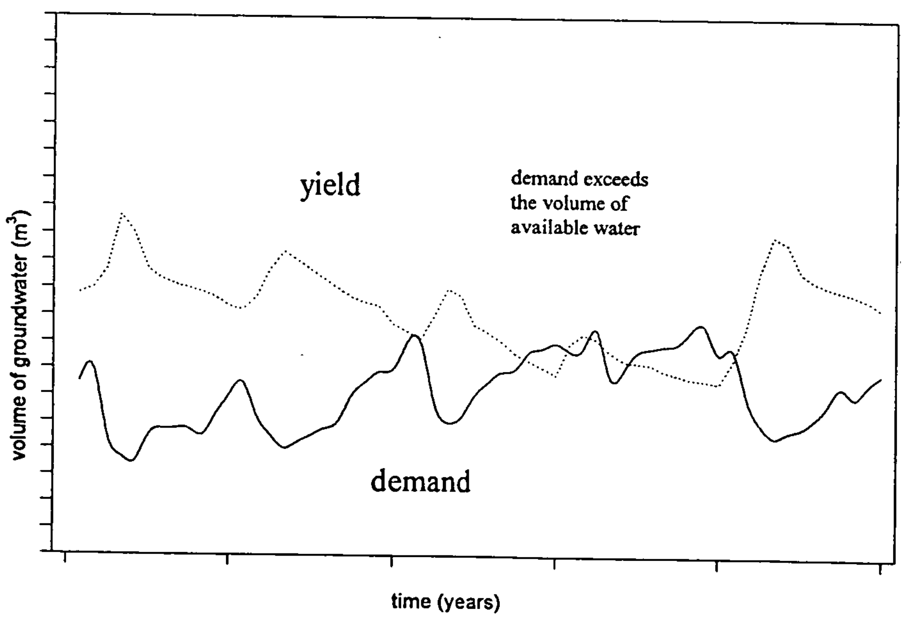

Figure 5 Fluctuations in the yield and demand of a borehole/well during a period of drought. This example illustrates a source that normally meets year round demand

accelerate (non-linearly) the shortage in supply. As the water levels fall and are drawn down by high pumping rates, the pump comes under a lot of stress and stands a greater chance of failing. The result of such a failure would be an increased demand on a neighbouring borehole/well with a corresponding increased stress (and probability of failure) on that borehole/well. And so the cycle continues.

The hydrogeology of the aquifer influences the amplitude of the yield fluctuations. If an aquifer is highly permeable and contains a high volume of groundwater, then borehole/wells can have high yields. In such a case the borehole/well is likely to meet even the high demands put upon it by drought. If the aquifer properties are poor, however, a borehole/well might be unable to meet even "normal" dry season demand. Longer term changes in climate (and therefore recharge) could put both the high and low yielding sources at risk.

Long term increases in demand can make a source vulnerable to drought that in the past was able to meet all the water demands put upon it. The seasonal and drought fluctuations in demand might historically have fallen well below the "water availability curve". A long term increase in demand, however, can eventually put the fluctuations above the curve so that demand will exceed supply.

Increasing changes in demand and decreasing yield should therefore be the most important factors to consider when endeavouring to manage groundwater in drought prone areas. Under different socio-economic and hydrogeological environments the variations in demand and yield will vary. Trying to estimate the amplitude and time period of these variations will help to manage groundwater more successfully in drought prone areas. Understanding the nature of demand and yield from individual sources can therefore hold the key to, preparing for, and coping with, drought.

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