



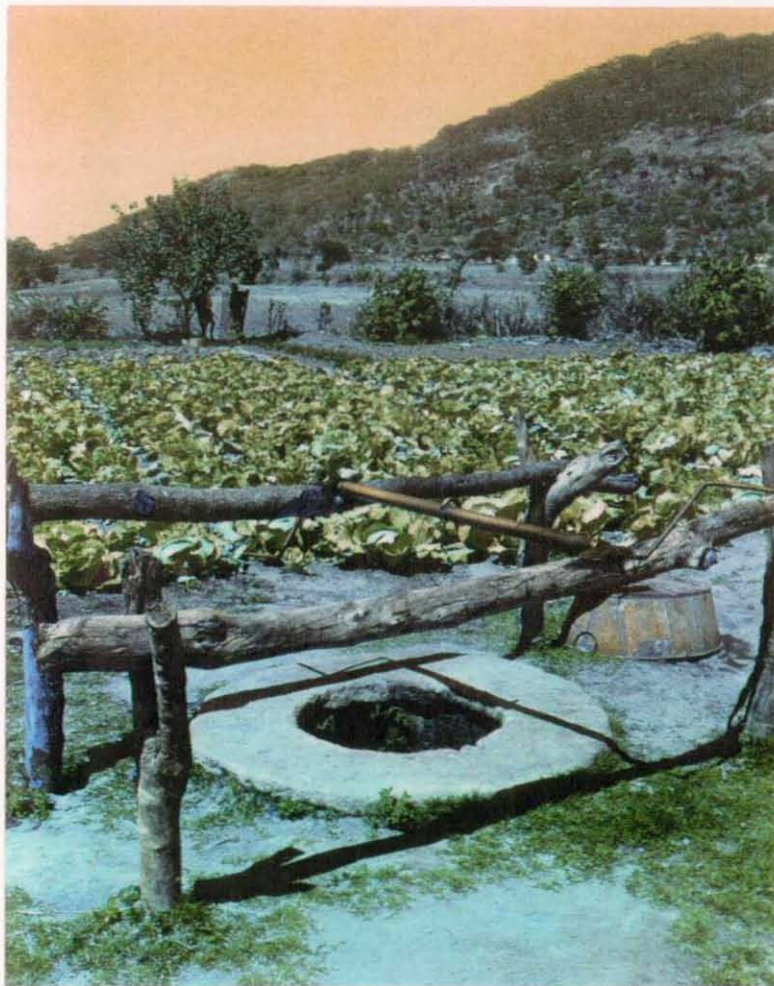
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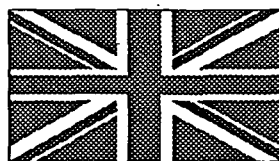
# SUSTAINABILITY OF YIELD FROM WELLS AND BOREHOLES IN CRYSTALLINE BASEMENT AQUIFERS

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# SUSTAINABILITY OF YIELD FROM WELLS AND BOREHOLES IN CRYSTALLINE BASEMENT AQUIFERS

D M J Macdonald, D M Thompson and R Herbert

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Traditional well, Romwe Catchment, Zimbabwe

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## EXECUTIVE SUMMARY

Large areas of the world are underlain by crystalline basement rock of igneous or metamorphic origin (Wright, 1992). For many people in arid and semi-arid regions the groundwater stored in these rocks is the only source of water for long periods of the year. This is particularly true for the rural population without access to piped water.

This project was undertaken to investigate the factors that control the yield from wells and boreholes in these aquifers and suggest methods of groundwater development to increase the probability that these yields are sustainable. The project concentrates on the crystalline basement aquifers of Zimbabwe, but many of the conclusions are applicable to other regions of Africa and the world. The project highlighted general issues relating to the sustainability of yield from wells and boreholes as well as producing specific findings with relevance to groundwater development programmes.

Although the storage of weathered basement aquifers is low relative to many other aquifer types due to limited vertical and lateral extent, typical long-term average volumes of water available at the end of the wet season (100 mm) are vastly greater than the 1-3 mm/a which it is estimated (Wright, 1992) would be required to bring the population of Africa up to the World Health Organisation recommended water supply of 25 litres/head/day. However, problems of groundwater availability and access in the shorter term complicate the picture. These problems arise due to two major constraints: the extended periods of below average rainfall that occur in arid and semi-arid regions which reduce the recharge necessary to replenish the limited aquifer storage; and the low permeability of basement aquifers which can cause significant dewatering of aquifers in the vicinity of pumping wells and boreholes.

Although, with the aid of hydrogeological expertise, boreholes may be drilled that allow abstraction of upwards of 150 m<sup>3</sup>/day from basement aquifers, the productivity of these aquifers is generally poor due to low permeability and saturated thickness of weathered material. In extreme cases these may be so low that the yield from wells may not even be sustainable over the period of one dry season. However, even relatively productive wells may suffer during periods of drought as seasonal replenishment of these low storage aquifers is essential. During these periods, problems of reduced storage are exacerbated by increased groundwater abstraction as alternative water sources disappear.

In regions affected by such conditions the siting and design of groundwater sources is crucial. Field programmes carried out in collaboration with two projects, funded at least in part by the Overseas Development Administration, were undertaken in the Lowveld of south-east Zimbabwe to investigate these issues further:

- i) a study was undertaken in a small catchment (4.6 km<sup>2</sup>) underlain by basement to investigate the groundwater flow system and the interaction of existing traditional wells. A collector well was constructed in the catchment in 1991. The work was undertaken as part of the Romwe Catchment Study, funded by the ODA Technology Development and Research (TDR) programme and run by the UK's Institute of Hydrology (IH), the Zimbabwean Department of Research and Specialist Services (DRSS) and the British Geological Survey (BGS).

A number of interesting results were obtained from this study, including:

- monitoring and testing of traditional wells showed a wide variability of well yield. The productivity correlated with the shallow weathered zone profile, itself dependent on the parent rock mineralogy. However, historical evidence suggested that the yield of all wells in the catchment suffered significantly from the drought of the 1980s and early nineties.

The vast majority of these wells can no longer be deepened as they are as far into the weathered zone as can be dug by hand;

- it was estimated that the abstraction from the collector well was greater than the total abstraction from all the wells in the catchment. Using estimates of aquifer storage and water-level fluctuation it was calculated that the total volume of water abstracted from the collector could be obtained within a cylinder of aquifer of a radius of 225 m. The collector well managed to maintain a supply of water to the population of the catchment and beyond throughout the recent drought;
  - a combination of the monitoring of piezometer water-levels and the analysis of the groundwater chloride balance showed that the weathering profile is also a major control on the groundwater recharge and that this correlates with the parent rock mineralogy. A value of long-term average recharge to the shallow weathered aquifer over the catchment as a whole was estimated at 17 mm;
  - the areas of higher well productivity and groundwater recharge can be identified from remote sensing images of soil cover. It is suggested that a technique for siting wells could be developed based on this finding.
- ii) a modelling exercise was carried out based on pumping-test data collected from nine sites where collector wells had been constructed as part of the "Small scale irrigation using collector wells" pilot project. This was an ODA funded Technical Cooperation (TC) project in collaboration with the Government of Zimbabwe and run by IH, BGS and the Ministry of Lands Agriculture and Water Development (now split into the Ministry of Lands and Water Resources and the Ministry of Agriculture).

This exercise showed that at sites underlain by basement aquifers:

- using exploratory drilling to identify the greatest thickness of saturated weathered basement aquifer could be a successful method for siting both wells and boreholes;
- effective screening of boreholes in the weathered zone could significantly increase yields;
- large-diameter dug wells constructed in the shallow weathered basement using the above method, unlike adjacent deep communal boreholes, were consistently able to provide an adequate amount of water for village domestic supply;
- there was a variable improvement in the productivity of large-diameter wells converted to collector wells. The percentage improvement ranged from 2% to 67%, with an average of 38%.

These studies have highlighted a number of useful techniques for improved siting of wells and boreholes. They have also shown the potential for developing the shallow weathered basement aquifer using large-diameter wells and collector wells. Evidence from the Romwe Catchment has shown that such sources do have the capability of providing a sustainable yield during drought periods.

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## 1. INTRODUCTION

### 1.1 The need for sustainable groundwater abstraction

Large areas of the world are underlain by crystalline basement rock of igneous or metamorphic origin (Wright, 1992). For many people in arid and semi-arid regions the groundwater stored in these rocks is the only source of water for long periods of the year. This is particularly true for the rural population without access to piped water. The basement is generally composed of two layers, the shallow weathered layer and the deeper bedrock, both of which have relatively low storage. As the storage in both layers is low and the extent limited, the groundwater resource within the formation is not large. Therefore, in arid and semi-arid regions, where the climate is unreliable, prone to long periods of below average rainfall, the groundwater resource and those that rely on it are under continual risk. The requirement for sustainable sources of water that can withstand these low rainfall, low recharge periods is essential. This project aims to review and investigate the factors important to the sustainability of yield from wells and boreholes in crystalline basement aquifers.

### 1.2 Definition of sustainability of yield

There are many factors which control the sustainability of a groundwater source for example the headwork construction, pump maintenance and water quality. In rural areas the participation and the sense of ownership of the local community that ensures responsibility will be accepted for pump repair and abstraction regulation is crucial. However, this study has restricted itself to factors which influence the quantity of water that can be obtained from the well or borehole in the long-term.

A well or borehole supplies a sustainable yield if the volume of water required by the population reliant on it is available throughout the dry season, and over periods of below average rainfall. If a groundwater source is not sustainable the yield will either become severely limited or the source may dry-up completely. Reduced availability of water can lead to: the loss of irrigated crops; a daily supply of water below levels adequate for health; people having to travel great distances for water; the use of alternative polluted sources of water; or the migration of peoples.

A key factor which determines whether a groundwater source will continue to sustain a sufficient yield is the water-level. The cause of decline in well water-levels can be separated into a number of components:-

- (i) **Regional decline:** groundwater gradients exist within aquifers as a consequence of sloping topography, areas of concentrated recharge and areas of discharge. A natural decline will occur during the dry season or over the long-term when recharge is not sufficient to maintain water-levels. The rate of the decline will depend on the aquifer transmissivity and storage coefficient and on the quantity of water discharged from the aquifer.
- (ii) **Well interference:** the influence that the abstraction from neighbouring groundwater sources has on the water-level in a well is dependent on the spacing of the wells, the aquifer parameters and the magnitude of the abstraction.
- (iii) **Well drawdown:** the drawdown in a well due to the abstraction from the well itself. This is dependent on the volume and pattern of abstraction, the design of the well or borehole and the nature of the aquifer.

If the magnitude of each of these components of drawdown is known then the underlying cause of decline of well yield can be understood and where possible actions introduced to mitigate the impact.

### **1.3 Aims of the project**

The project aims to investigate the factors that control the yield from wells and boreholes in crystalline basement aquifers and suggest methods of groundwater development that increase the probability that these yields can be sustained. This includes recommendations on the siting and design of groundwater abstraction sources. The project concentrates on the crystalline basement aquifers of the arid and semi-arid regions of Zimbabwe, but many of the conclusions are applicable to other regions of Africa and the world.

To investigate the controls on well yield, work was carried out in a small catchment (4.6 km<sup>2</sup>) in the Lowveld of south-east Zimbabwe. The work was part of an ongoing study of the catchment, funded by the ODA Technology and Development Research (TDR) programme and run by the UK's Institute of Hydrology (IH), the Zimbabwean Department of Research and Specialist Services (DRSS) and the British Geological Survey (BGS). The study is described briefly in Chapter 3 and the results relating to this project are presented in Chapter 4.

As the result of a number of projects, funded at least in part by the ODA, ten collector wells have been constructed in recent years in the Lowveld of south-east Zimbabwe. Eight of these wells were constructed between 1992 and 1995 as part of an ODA funded Technical Cooperation (TC) project in collaboration with the Government of Zimbabwe and run by IH, BGS and the Ministry of Lands Agriculture and Water Development (now split into the Ministry of Lands and Water Resources and the Ministry of Agriculture). The project is described briefly in Chapter 3. A component of this project was a comparison of the sustainable yields of a number of different well types at each collector well site using the results of pumping-tests, field monitoring data and model simulations. The analysis of the data and the modelling, which relates to the affect of well design on sustainability, was carried out in collaboration with the "sustainable yield" project and is described in Chapter 5. Data is also included from the Romwe catchment, where a collector well was constructed in 1991.

The report also contains, in Chapter 2, a review of the hydrogeology of crystalline basement aquifers. In Chapter 6 the results of the project are discussed and in Chapters 7 and 8 respectively the conclusions and recommendations are presented.

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.

## 2. REVIEW OF THE HYDROGEOLOGY OF CRYSTALLINE BASEMENT AQUIFERS

Large areas of the world are underlain by crystalline basement rocks of igneous or metamorphic origin (Wright, 1992). Significant areas exist in sub-Saharan Africa, South America and Asia. Africa is distinctive in the grouping because of the continent's very dispersed rural population which in combination with the poor economic base, is responsible for the small scale of existing groundwater development, currently almost wholly for domestic supply or livestock use (Wright, 1992). In many of the areas of Africa underlain by crystalline basement the water stored within the rock is the major source of water. In tropical regions groundwater is often a safer source of water than surface water bodies; in arid and semi-arid regions groundwater may be the only source of water during the long dry season.

In Africa crystalline basement rock is primarily of Precambrian age and granitic or gneissose in type (Clark, 1985). The basement aquifer is formed due to the effects of weathering and tectonic forces on the parent rock. The aquifer can be simplified to a two layer system: the shallow layer (regolith), and the deeper bedrock. The sustainable yield of wells and boreholes is dependent in varying degrees on the nature of the basement, the groundwater recharge and the design of well used to exploit the groundwater resource. These aspects will be discussed further in this chapter.

### *Regolith*

The regolith can be sub-divided into the collapsed zone (or residual soil) and the underlying saprolite (Figure 2.1). Saprolite is derived from in situ weathering of the basement rock and is disaggregated. Weathering is more advanced in the vadose zone and within the zone of water-table fluctuation, and therefore it is the upper part of the saprolite that will be more weathered, with a higher proportion of secondary clay minerals. As the lower saprolite is in a less advanced state of weathering it has more of the primary clay minerals. The collapsed zone develops from the saprolite by further dissolution combined with other chemical, physical and biological processes. It includes soil and other layered features such as laterites, calcretes, illuviated clay layers and stone lines. Where weathering is particularly well developed, as in areas of the African erosion surface, the saprolite collapse can be substantial, resulting in areas of land subsidence. Colluvial distribution of residual materials downslope results forming features commonly known as dambos. These dambos cover a large area of Africa, approximately  $1.3 \times 10^4$  km<sup>2</sup>. The groundwater flow system within dambos has been a subject of much research (McFarlane, 1992).

In addition to the age of the erosion surface, the degree of weathering of the basement rock is dependent on the mineralogy, texture and structure of the parent rock (Jones, 1985) and the groundwater recharge and throughflow (Acworth, 1987). These are linked with the following factors:

- basement geology
- tectonic history of the locality
- climate, past and present
- local relief

As a result the weathering profile may vary considerably both on a regional and local scale.

### *Bedrock*

The bedrock aquifer is formed by fracturing caused by decompressional and tectonic forces and by primary weathering of the upper section (just below the regolith), referred to as saprock (Figure 2.1). The weathering that forms the saprock takes place along sub-horizontal and sub-vertical fractures. The transition between the saprock and the above saprolite depends on the rock texture, being more gradual in finer-textured rocks (Chilton and Foster, 1995). In granitic rock it is likely to occur over smaller depths than in metamorphic

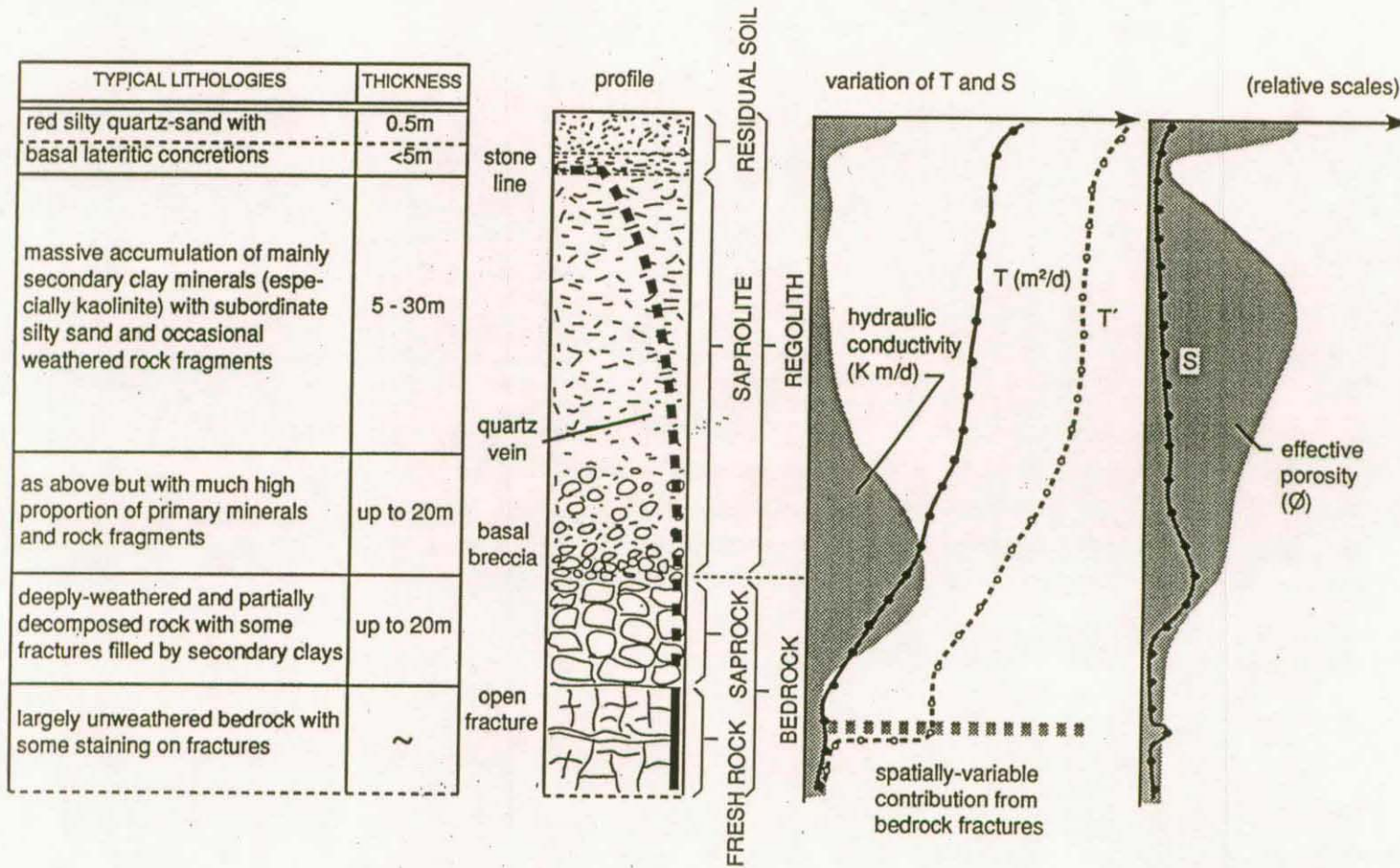


Figure 2.1 Conceptual hydrogeological model of weathered crystalline basement aquifer in Africa (after Chilton and Foster, 1995)

rock. The transition from saprock to the fractured bedrock is also generally gradual though laterally the zone of transition may fluctuate due to zones of denser sub-vertical fracturing or banding in the rock.

Evidence has been given for varying depths of fracturing in bedrock. Houston (1992) reports that borehole drilling in crystalline basement in Zimbabwe showed that 87% of the productive fissures in the bedrock were found within its top 20 m. Significant fracturing can also be found in the contact zone of sub-vertical intrusions. However, overall there is significant spatial variability in the productivity of bedrock aquifers.

#### ***Aquifer properties of the basement aquifer***

The vertical profiles of hydraulic conductivity, transmissivity, effective porosity and storage for the regolith and the fractured bedrock are shown in Figure 2.1. The upper layer of the collapsed zone is typically sandy on watersheds with sandy clays and clays on the valley bottoms. The hydraulic conductivity and the storage is high. This contrasts with the basal lateritic concretions beneath.

Permeability in the basement initially increases with weathering. However, as the primary clay minerals are further weathered to secondary clay minerals, which do not retain the texture and porosity of the original disaggregated regolith, the permeability reduces. Some minerals, in particular ferromagnesian minerals, will weather more easily to secondary clay minerals. The upper saprolite, though high in storage has a low hydraulic conductivity due to the higher proportion of secondary clay minerals. However, in some regions where more aggressive weathering has taken place the secondary minerals may dissociate resulting in a return to higher hydraulic conductivity (McFarlane, 1992). The less developed weathering in the lower saprolite produces a higher hydraulic conductivity especially in the breccia at its base. Wright (1992) gives an average hydraulic conductivity for the regolith as a whole as less than 0.5 m/d; Chilton and Foster (1995) suggest 0.01 m/d. The transmissivity of the regolith depends on its saturated thickness. The average saturated thickness of regions can be quite variable, for example in the south of Zimbabwe it is typically 10 m, whereas in Malawi, where the erosion surface is older and therefore the depth of weathering greater, typically 20 m. The porosity of the regolith as a whole has been estimated at 20-40% (Wright, 1992): the values of specific yield (drainable porosity) are less well known, however, these are probably within the range 1-10%. A conservative estimate of the average drainable height of water from the weathered zone in an area such as Southern Zimbabwe would therefore be 100 mm.

The saprock has a relatively high hydraulic conductivity and this in combination with the base of the saprolite forms the most consistently productive zone of the basement rock. The hydraulic conductivity of the saprock can on occasions be reduced, however, by the illuviation of secondary minerals from the saprolite. The hydraulic conductivity of the bedrock is spatially variable, depending on the degree of fracturing. The hydraulic conductivity of productive zones has been given within the range 0.01-3 m/day (Wright, 1992). As the storage of these aquifers is very low (<1%) it is suggested that, where productive boreholes exist, there is good connectivity with the high storage of the regolith above (Barker *et al.*, 1992).

Crystalline basement aquifers are, on the whole, typically semi-confined systems. The aquifer condition is dependent on the depth of weathering and the level of the potentiometric surface. Where the potentiometric surface is situated within the upper section of the saprolite the aquifer is likely to be semi-confined or occasionally confined (Acworth, 1987). Where rainfall is moderate to high (>600 mm) the water-table is likely to occur at depths of less than 10-15 m. In more arid regions, such as much of Botswana, the water-table may be permanently below the regolith or fall below in the latter part of the dry season.

#### ***Recharge processes***

The storage of basement aquifers is relatively small and therefore highly reliant upon the annual rainfall, which in arid and semi-arid regions is largely restricted to one period of the year. It is thought that significant recharge to these aquifers only occurs in response to intense storms or periods of prolonged rainfall necessary to overcome large soil moisture deficits that develop within the dry season (Meigh, 1988). Recharge may

occur by infiltration through the soil layer (diffuse recharge) or via surface water bodies or linear features (localised recharge).

Diffuse recharge is dependent to a degree on the land cover. Where natural vegetation has been cleared and land cultivated, crusting may occur at the soil surface and reduce infiltration and recharge. A proportion of the water that does infiltrate through the near-surface zone may not reach the deep aquifer. A combination of the low permeability of the upper saprolite and the higher permeability of the upper layer of the collapsed zone can induce significant lateral flow (interflow) which may be discharged downslope through seeps or as baseflow to rivers or streams. In the wet season a perched water-table may develop within the upper saprolite.

There are many locations at which localised recharge can take place, streams, rivers and ponds being the most obvious. Other locations include: the base of hills and bare outcrops, which act as effective catchments for rain; zones of dense sub-vertical fracturing; the contact zone with sub-vertical minor intrusions; behind contour bunds; and localised lows in the topography.

Methods to estimate diffuse recharge and localised recharge via surface water bodies are described in Simmers (1988) and Lerner et al (1990), however, the complexities of crystalline basement aquifers make these methods difficult to apply. Accurate estimates of recharge require detailed studies that should employ a number of methods, such as chloride balance and river baseflow measurements (Houston, 1988), to confirm results. Further, regional estimates of recharge are difficult to obtain as they are dependent on spatially variable factors such as climate, relief, soil type and land use.

Estimates of recharge taken from a number of studies are given in Table 2.1. These are given as percentages of the mean annual rainfall.

**Table 2.1 Groundwater recharge to crystalline basement aquifers as a percentage of the mean annual rainfall**

Location	Annual rainfall (mm)	Percentage of annual rainfall
Malawi <sup>1</sup>	1700	11-19
Nigeria <sup>2</sup>	950	10-17
Zimbabwe <sup>2</sup>	600	2-5
Zimbabwe <sup>3</sup>	600	0.5-6

<sup>1</sup> Wright (1992)

<sup>2</sup> Houston (1988)

<sup>3</sup> Meigh (1988)

The estimates in Table 2.1 suggest that groundwater recharge, as a percentage of mean annual rainfall, decreases as annual rainfall decreases. Work carried out by Houston (1988) in Masvingo Province in south-east Zimbabwe in which recharge was measured using baseflow analysis, chloride balance and soil moisture budgeting showed that when the annual rainfall was less than 400 mm the recharge was almost negligible. However, temporal distribution of rainfall will also have great significance.

### **Exploration**

Low cost and low technology methods can be employed to obtain levels of abstraction from basement aquifers sufficient for small villages. The potential for abstracting large quantities of water, however, is generally low. Their low transmissivity and storage coefficient restricts the volumes of groundwater that can be abstracted by causing the significant drawdown of water-levels in the vicinity of wells and boreholes. Further, aquifers may be limited in extent where less weathered rock forms barriers to lateral flow or where bedrock fracturing is localised. These problems are exacerbated in arid and semi-arid regions by the lack of reliability of rainfall.

Although the potential to exploit basement aquifers may be low it represents in many cases the only source of relatively cheap and potable water. It is estimated that only 30% of the rural population of sub-Saharan Africa have access to a clean potable water supply of 25 litres per head per day, the minimum quantity specified by the World Health Organisation. However, it has been calculated that the equivalent of only 1-3 mm/a of areal recharge would be required to meet the demand. Compared with the range of values of recharge of 30-150 mm/a (where annual rainfall is 500-1000 mm) quoted in Wright (1992), this is not significant.

To achieve the required levels of abstraction, methods such as geophysical surveying are used to identify the preferred sites. Geophysical techniques include seismic refraction (Davies, 1994), vertical electrical sounding, resistivity and EM surveying (Hazell *et al.*, 1992). These methods are used to locate lineaments and areas of greatest regolith thickness in the weathered basement. The siting of groundwater sources with geophysics does require a substantial input of expertise and it is recommended that its use is only considered in areas where the potential is low and the need greatest.

### **Exploitation**

Recent water supply projects have shown varying degrees of success in exploiting basement aquifers. Wright (1992), based on the criteria of achieving a yield greater than 0.25 l/s (suitable for a handpump), suggests a typical success rate for many African countries of 70-80%. Handpumps are the most widely employed abstraction method in development projects, being an appropriate level of technology for rural Africa. The level of success falls when larger volumes of water are required. Houston (1992) compares two rural water supply projects, in Zimbabwe and in Nigeria where groundwater was developed with boreholes. In Zimbabwe, the required abstraction rate was 0.2 l/s. The success rate was over 70%. In Nigeria, where electric submersible pumps were fitted to completed boreholes, the required abstraction was 1 l/s. The success rate here was less than 45%.

The zone of the basement aquifer being exploited is dependent on the design of the groundwater source. The weathered basement has traditionally been exploited by shallow hand-dug wells with diameters of typically 1-1.2 m. The depth of this type of well is restricted by the hard rocks below the regolith (as the wells are usually dug using hand tools) and by the water-table. Large-diameter dug wells (constructed within groundwater development programmes) tap the regolith and the saprock. Their larger volume acts as a reservoir that can be pumped during the day, recharging overnight. Recently collector wells have attracted considerable interest as a source. This is a large-diameter well with boreholes drilled laterally out from its base to tap the high permeability layer at the base of the saprolite. The design of groundwater source applied most commonly by local government departments and NGOs is the slim borehole. Boreholes are typically 50 m in depth. Houston and Lewis (1988) suggest that the most productive zone of the bedrock is within the top 20 m (including the saprock). Cost-effectiveness falls rapidly if the borehole is drilled to greater depths.

Though the type of well is dependent on local conditions, rarely due to a lack of understanding, do development organisations have a flexible approach to choosing the well design. This may result in low and unsustainable yields where, for example, a borehole is drilled into a bedrock aquifer of low transmissivity and the potentially productive regolith is cased off (Howard and Karundu, 1992), or a dugwell is constructed in



the regolith where the saturated thickness of the weathered layer is small. Acworth (1987) and Lovell *et al.* (1995) describe more pragmatic approaches to groundwater development.

### **3. PROJECT BACKGROUND: ASSOCIATED WORK IN SOUTH-EAST ZIMBABWE**

A catchment case study and a comparative study of well design have been carried out to illustrate and investigate further the causes of unsustainable yield from wells and boreholes in crystalline basement aquifers. These studies are both located in the south-east of Zimbabwe, in a region of relatively low altitude, known as the Lowveld (see Figure 3.1). This chapter describes the environment of the Lowveld and the ongoing work there with which this project is associated.

#### **3.1 The Lowveld of south-east Zimbabwe**

##### *Climate*

The Lowveld of Zimbabwe is defined as land with an altitude less than 900 m above sea-level. The climate is semi-arid, characterised by low rainfall and high temperatures. The temperatures range from 16°C in June and July to the hottest period prior to the rains in October, when temperatures may be in excess of 35°C. The rainfall averages 450 mm/a, ranging from approximately 250 mm/a to 750 mm/a. The winter season of May and September, is generally dry with the bulk of the rains falling between November and March. Figure 3.2 shows the variation of yearly rainfall totals from the long-term mean over the past 42 years from three sites in the Lowveld. This highlights the period of below average rainfall that occurred in the 1980s and early 1990s culminating in the major drought of 1991/92. The rainfall figures suggest an approximate 20-year cycle in rainfall.

##### *Geology*

The geology of the region of the Lowveld within the project area (see Figure 3.3) is primarily metamorphic rock of Precambrian age, formed within the northern marginal zone of the Limpopo Mobile Belt (Robertson, 1974). The project area also includes to the north the granites and greenstone belts of the Zimbabwe Craton and to the south the Karoo basalts. A gradual transition exists from the granite-greenstone craton to the high-grade metamorphic rocks of the marginal zone. The metamorphic rocks are mainly granulite gneisses. These have a north-east to south-west trend. The regolith of the basement rock is typically less than 20 m thick (Wright 1989) but is generally thicker in the gneisses than in the granites (Barker *et al.*, 1992). The principal clay mineral is kaolinite.

##### *Land use*

The majority of the land in the Lowveld is taken-up by extensive cattle and game ranching and communal lands, with some irrigated plantation agriculture, principally sugar cane. The communal lands are farmed on a subsistence basis, both arable and livestock. Rainfed crops such as maize, groundnuts, sunflowers, sorghum and cotton are grown, although yields tend to be poor due to unreliable rainfall. Small-scale irrigation of gardens using groundwater also takes place for vegetables such as tomatoes, onions and leaf vegetables. In the past decade the resettlement of land has resulted in the cultivation of larger areas and the removal of many trees. This change in land use has caused an increase in the problem of soil erosion. It has also created the need for new sources of water for the newly settled population.

#### **3.2 Associated work in south-east Zimbabwe**

This project was carried out in collaboration with two other projects located in the Lowveld of south-east Zimbabwe. The field investigations and the aims of the "sustainable yield" project are integrated with these projects. The two projects are described in the following sections.

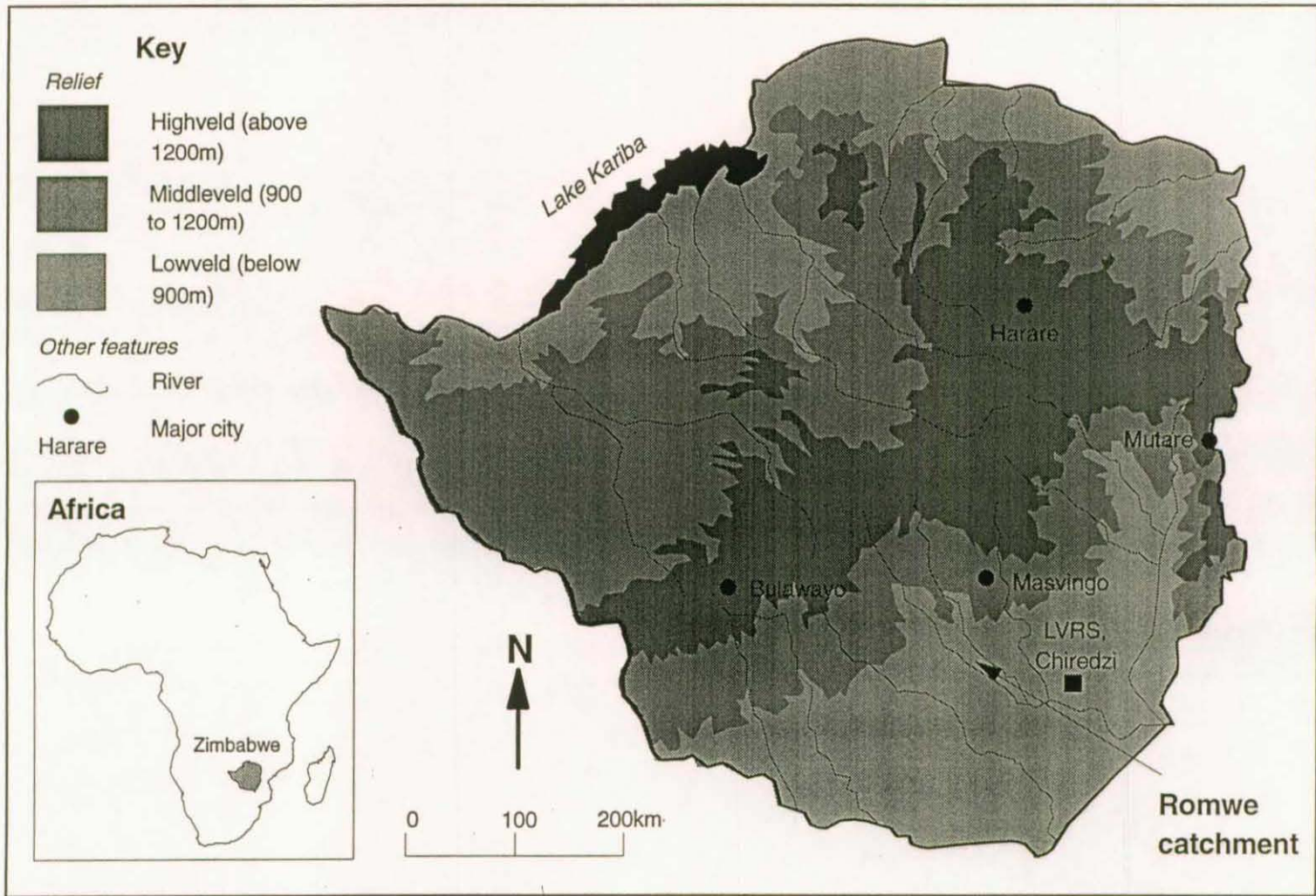


Figure 3.1 Physical map of Zimbabwe (after Butterworth *et al.*, 1995)

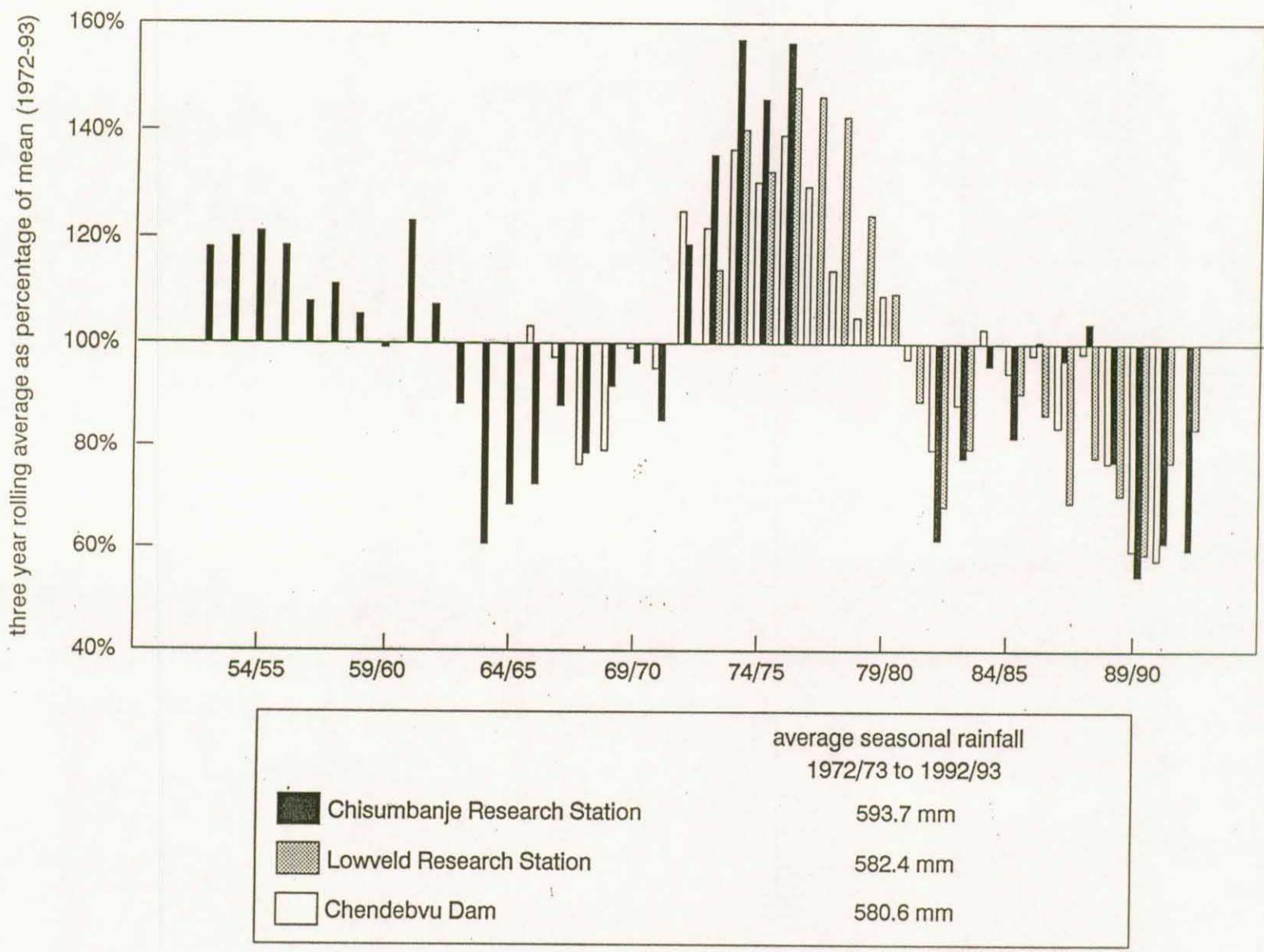


Figure 3.2. Percentage variation of the three year rolling average of yearly rainfall from the long-term mean (1972/73 to 1992/93) at three sites in south-east Zimbabwe

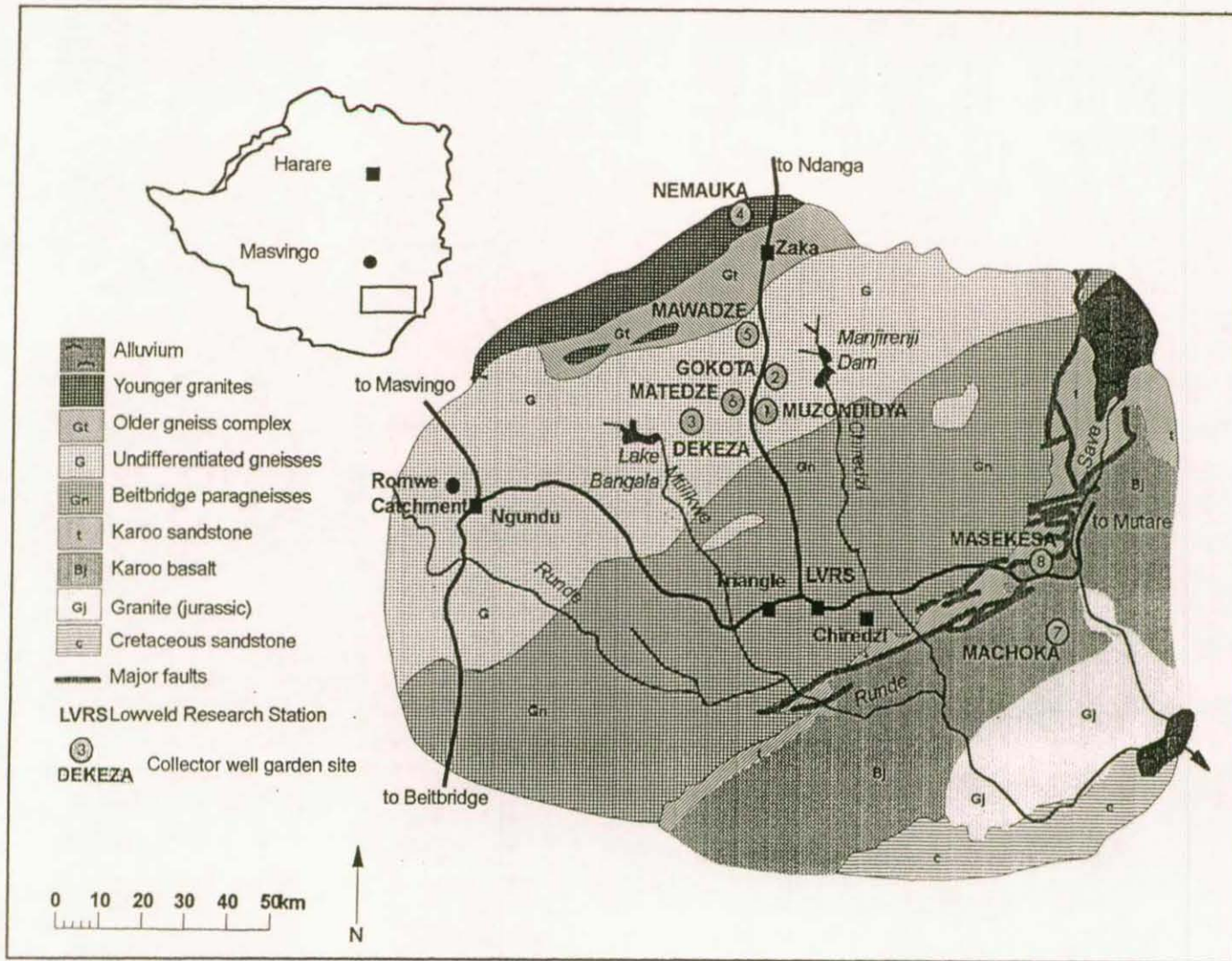


Figure 3.3 Regional geology of the field area including location of Romwe Catchment and collector well sites

### ***Small-scale irrigation using collector wells***

Wells and boreholes within crystalline basement can generally support the domestic water needs of families within the rural communities of Africa. The long-term sustainability of these traditional sources, however, is questionable when larger quantities of water are required. In 1988 IH and BGS, along with Zimbabwe's Ministry of Lands Agriculture and Water Development (MLAWD), undertook a project to study the feasibility of using the shallow aquifer as a source of water for irrigating allotment-type gardens in rural communities. It was felt at that time that collector wells had the greatest potential to supply water for domestic uses, livestock water requirements and still provide sufficient water for irrigating gardens. An experimental study was set-up at the Lowveld Research Station near Chiredzi and a pilot community garden in the Chivi communal area south of Masvingo. The community garden was up-and-running by 1991 and consisted of 46 families from the villages (or kraals) of Tamwa, Sihambe and Dhobani. The collector well supplies an adequate amount of water for all needs and the scheme is flourishing. During the drought of 1991/92, as many traditional wells dried-up in the locality, the collector well was used heavily and became a vital source of water for many families in the surrounding area.

Largely as a result of the success of the pilot garden at the Tamwa, Sihambe and Dhobani villages site, a pilot project was devised to supply a further six schemes at sites in south-east Zimbabwe, with the objective to identify a basis to replicate these on a wider scale. This technical cooperation project was funded jointly by the ODA's British Development Division Southern Africa and the Government of Zimbabwe. Although the source of water at all sites is the collector well, a component of this pilot study looked at the cost-effectiveness and long-term sustainability of other point sources; large-diameter wells, boreholes sited by exploratory drilling and screened in the shallow weathered layer and deep boreholes drilled into the fractured bedrock and cased in the regolith.

To compare the sustainability of the various well types at each site a series of pumping-tests were undertaken and the results used to model the well performances. The analysis was carried out in collaboration with the "sustainable yield" project. This work is presented in Chapter 5.

In addition to the initial six sites, another two have been set-up in the Sangwe region of south-east Zimbabwe, funded by the charity Plan International. Unlike the aforementioned sites the underlying geology is Karoo basalt. The results from these sites have also been included in Chapter 5.

The location of the eight sites and the initial scheme, are shown in Figure 3.3. One site is located on the Younger Granite formation, six on the Undifferentiated Gneisses and two on the Karoo Basalts.

### ***The effect of land management on groundwater recharge***

Price (1993) describes the "deterioration" of the Tamwa/Sihambe/Dhobani area (to be referred to as the Romwe catchment), the site of the original ODA-funded collector well garden, since its settlement in the 1950s. Prior to settlement the hills and valley bottoms were wooded apart from several grassy areas which remained wet for almost all the year. These wet areas have dried-up in the last two decades and the wooded valley bottoms have almost completely been cleared. Though neither tributaries to, nor the main river within the catchment flowed for the whole of the dry season, pools formed which lasted sometimes up to seven months into it. Springs that supplied the tributaries have not operated since the local drought in the eighties and early nineties.

The catchment has seen a rapid growth in the number of traditional wells in the last two decades. Price (1993) also reports recollections from local people that suggest water-levels have fallen over the years in two of the oldest wells in the catchment by approximately 4 and 7 metres respectively. A fall in well water-levels may be due to one or a number of reasons:

- a rise in population has resulted in an increase in groundwater abstraction which has caused wells to dry-up, requiring more wells to be dug and existing wells to be deepened;

- a reduction in groundwater recharge due to a combination of long-term decline in rainfall and change in land use, resulting in falling water-levels over the whole catchment;
- a medium term reduction in groundwater recharge due to an extended period of below average rainfall.

To examine the causes of the problems a collaborative study has been undertaken by IH, DRSS and BGS in the Romwe catchment. The IH and DRSS component of the study, "the effect of land management on groundwater recharge", funded by the ODA TDR programme, is looking in detail at the recharge processes taking place in the area and the effect that land use change may have had on them. It is also studying the catchment hydrology and the socio-economic impact of land management practices. As part of this work all aspects of the water balance are being monitored.

The BGS component of the study (a separately funded ODA TDR project), which is described in Chapter 4, looks specifically at the causes of falling water-levels in wells and investigates to a degree the spatial trends in groundwater recharge. It is hoped that this work, which restricts its efforts to one small area, will allow a greater understanding to be obtained of the detail of the groundwater flow system within crystalline basement aquifers and hence the factors controlling the sustainability of yield from wells and boreholes.

The catchment study is based on a surface water catchment. The catchment is named after the large rocky outcrop which overlooks it, known locally as Romwe. The Romwe catchment study as a whole, and the BGS component specifically, is described in Chapter 4.

## 4. CASE STUDY: ROMWE CATCHMENT

### 4.1 Catchment description

#### 4.1.1 Location

The catchment is situated in Masvingo Province approximately 86 km south of Masvingo and 105 km west of Chiredzi, at latitude 20°43'S and longitude 30°43'E (Figure 3.3). The catchment is in wards 23 and 25 of the southern part of Chivi District. Two villages are partly contained within the catchment, Sihambe, situated on the northern side and Dhobani on the southern side. Homesteads are spread along the base of the bounding hills that run west to east along the catchment. There are 32 homesteads within the catchment and an estimated population of between 200 and 250 people. Figure 4.1 shows a map of the locality. A more detailed description of the catchment can be found in Butterworth *et al.* (1995).

#### 4.1.2 Relief and hydrology

The surface water catchment is approximately 2.75 km long (east to west) and varies from 1.5 to 2.5 km across (Photographs 4.1 and 4.2). The total area is 4.6 km<sup>2</sup>, approximately 1.8 km<sup>2</sup> of which is land suitable for cultivation. This cultivated land is bounded by the base of the surrounding hills. The catchment includes: to the south and to the north-east, forested hills; in the north-west corner, a large rocky outcrop (inselberg); to the east of the inselberg, smaller bare outcrops; and to the north, a broken line of smaller outcrops. The altitude is between 695 and 955 metres above sea level, the highest point being on the summit of the hills on the southern side. The valley slopes have an average gradient of 4° and the hill slopes rise at approximately 30°. The outflow of the catchment is to the west. The main stream runs roughly through the centre of the catchment with the majority of tributaries coming from the southern bounding hills.

#### 4.1.3 Rainfall

Reliable rainfall data have been collected in the catchment over the past two wet seasons. The rainfall data used prior to November 1993 was collected at Chendebvu Dam, approximately 12 km from the catchment. Figure 4.2 shows a record of daily data from July 1992 to June 1995. Estimated and measured yearly rainfall totals for the catchment over the past three years are 501, 661 and 725 mm. In 1993/94 the majority of the rainfall occurred early in the year (November-December) and as a number of large rainfall events. In 1994/95 the rainfall was more evenly distributed, though a major storm of 141 mm did occur in February 1995.

#### 4.1.4 Geology

Romwe is situated within the Undifferentiated Gneiss formation of the northern margins of the Limpopo Mobile Belt. The Undifferentiated Gneiss is a granulite gneiss which trends ENE-WSW to SW-NE; the topography shows the same lineation. A geological map of the Romwe catchment is shown in Figure 4.3. A detailed description is given in Butterworth *et al.* (1995) but a summary is given here.

A strongly developed gneissic foliation dominates the trend of the topography in the Romwe catchment making it easy to recognise the major structural features from aerial photographs. The most obvious structural feature is a synform, the axis of which passes through the hills to the north-east before swinging round to pass in an E-W direction through Romwe. Fractures and faults, at all scales, are numerous throughout the area. Most trend in a NNW direction, normal to the gneissic foliation and are generally sub-vertical. These fractures may increase the local permeability of the basement; it is also relevant to note many of the springs recorded in the area are associated with faults. A few of the fractures and faults are intruded by dolerite dykes ranging from 4-10 m in width.



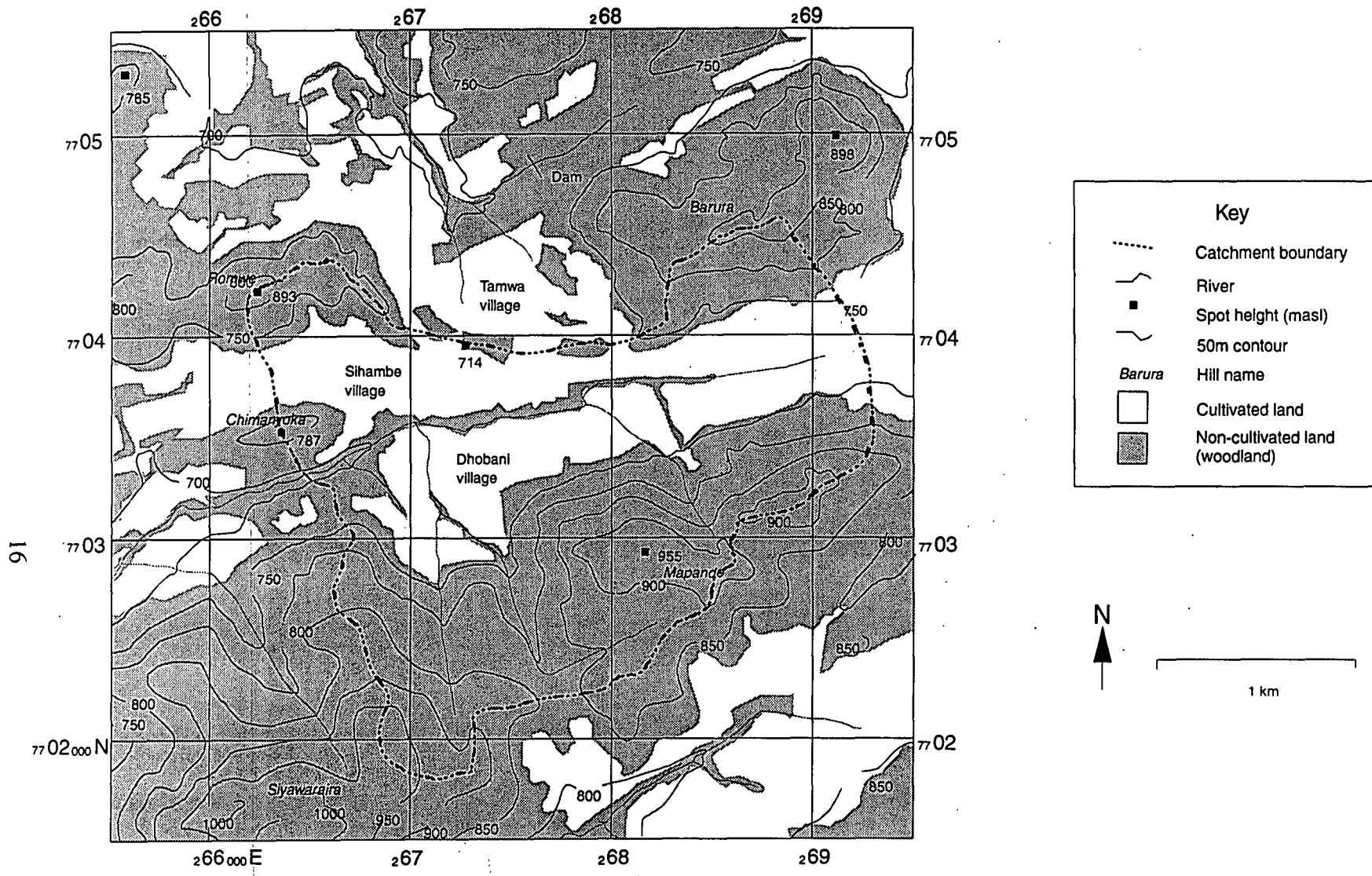
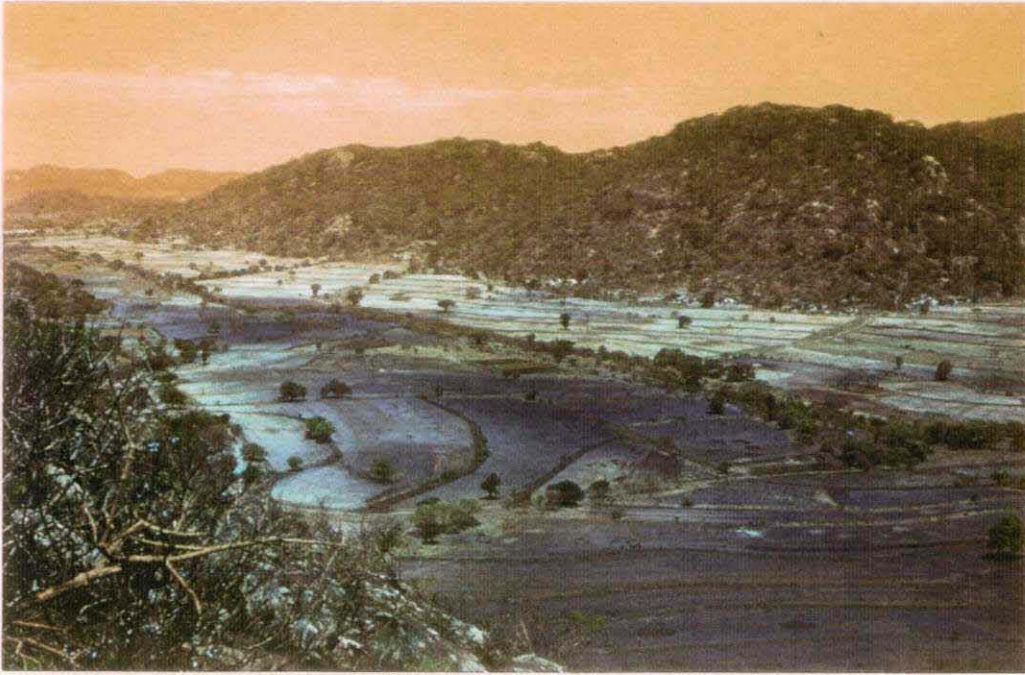
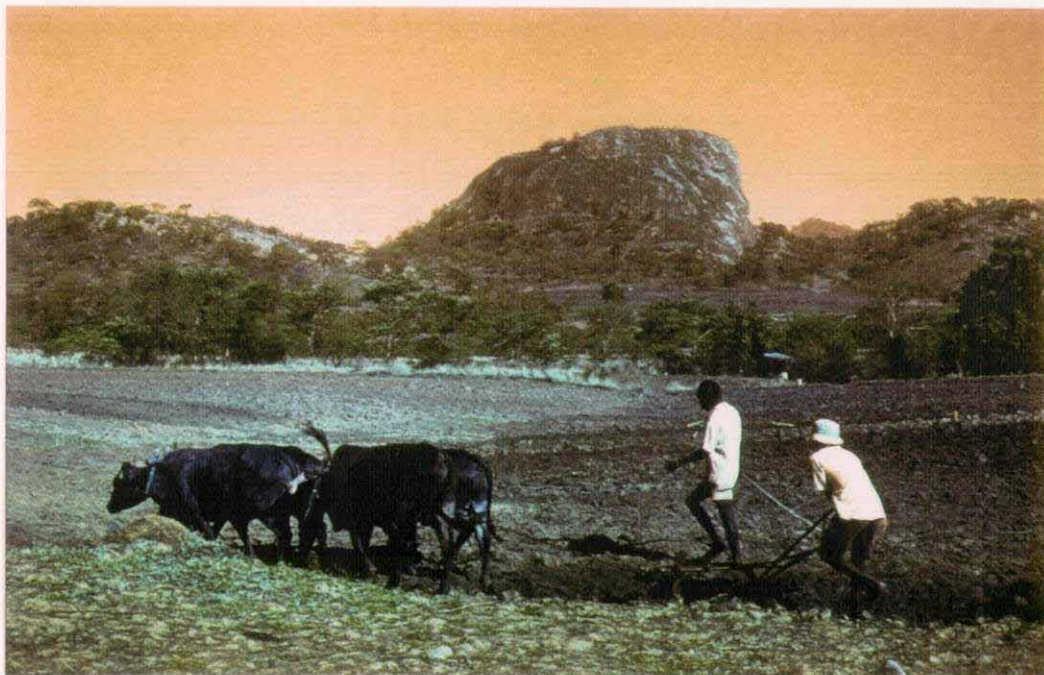


Figure 4.1 Romwe Catchment, topography, hydrology and land use (after Butterworth *et al.*, 1995)



Photograph 4.1 View, north-west to south-east, of Romwe Catchment from Romwe inselberg



Photograph 4.2 View, south-east to north-west, of Romwe inselberg from southern side of Romwe Catchment.

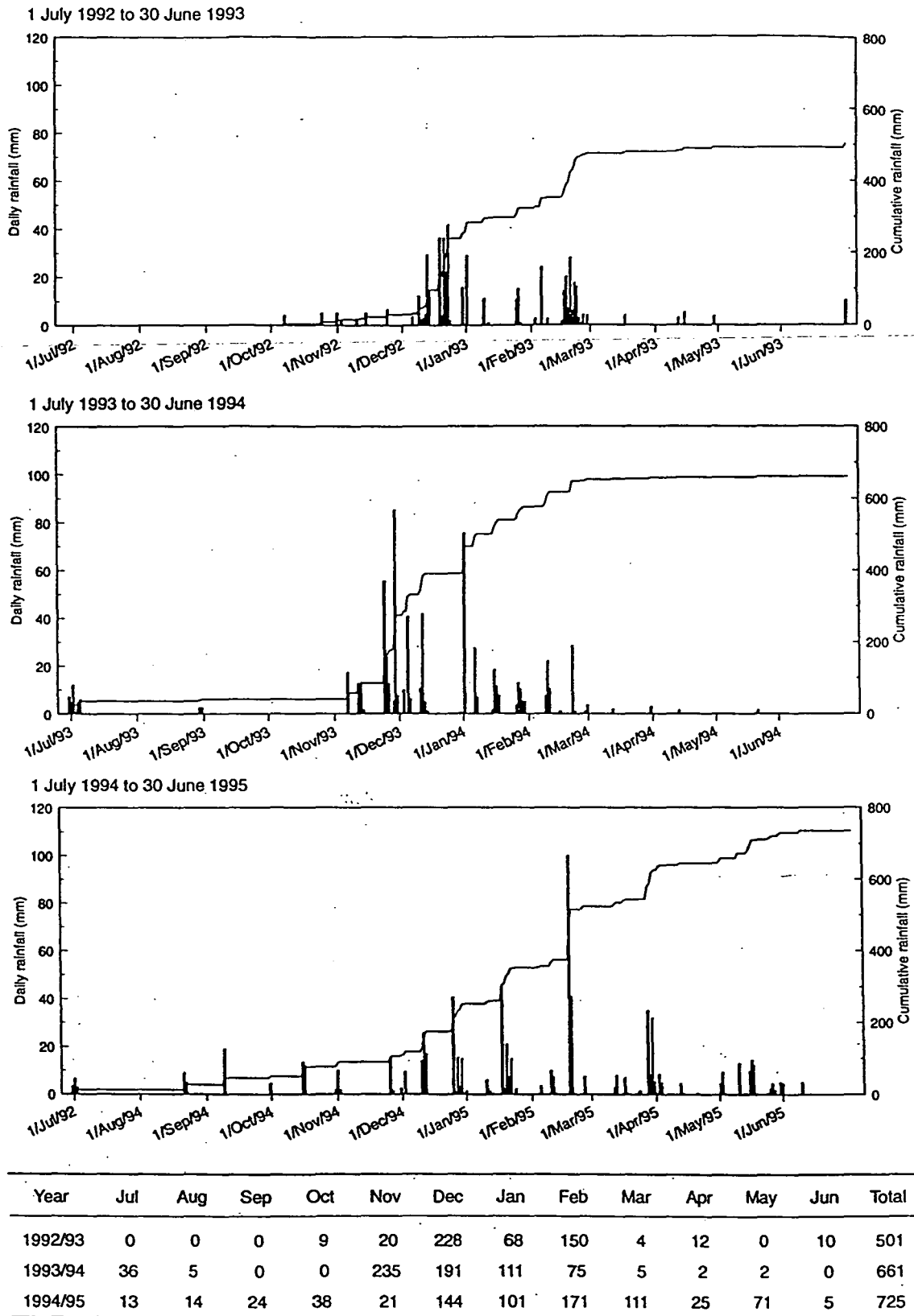


Figure 4.2 Daily rainfall and seasonal cumulative rainfall for Romwe Catchment 1992/93 to 1994/95 (after Butterworth *et al.*, 1995)

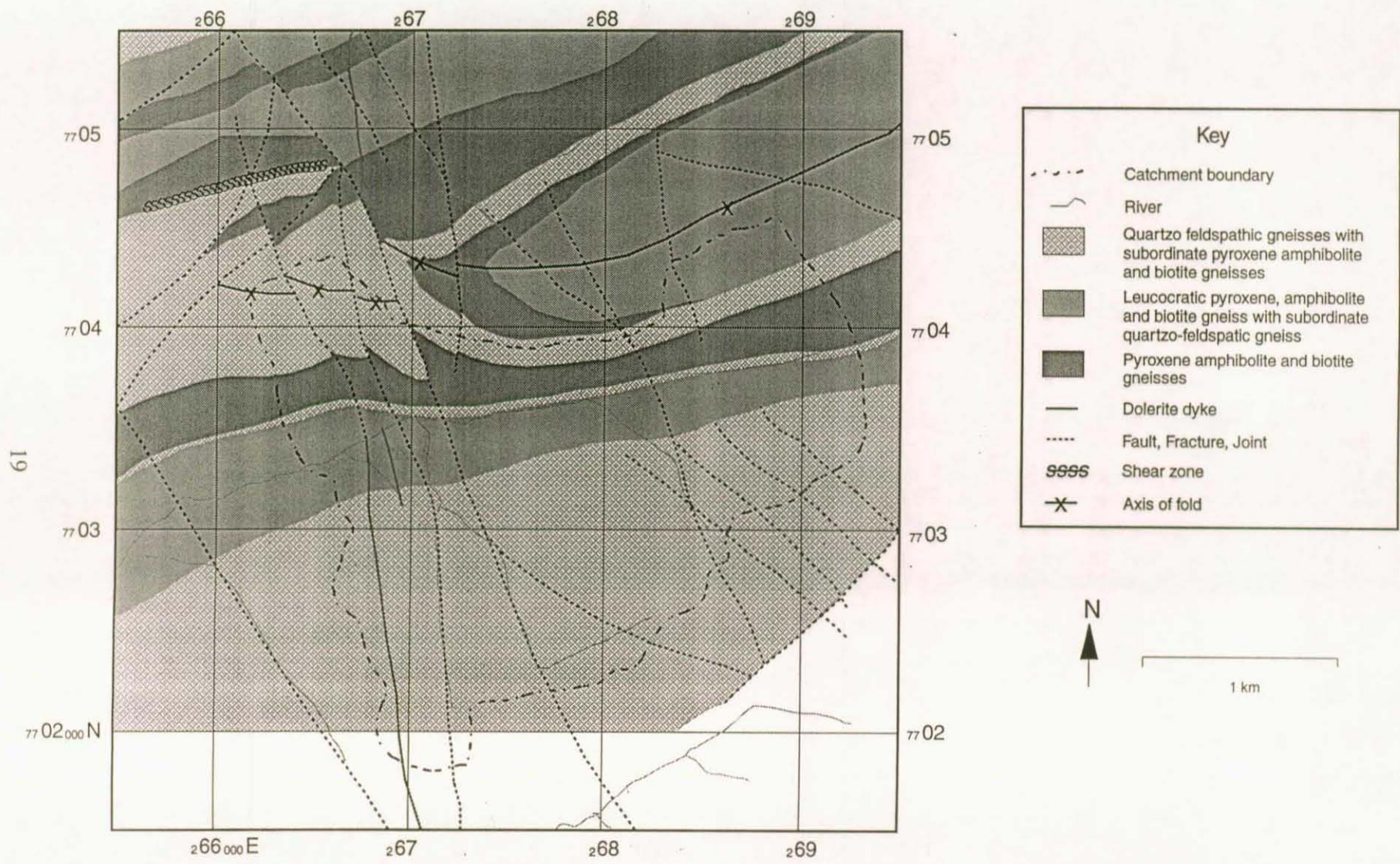


Figure 4.3 Geological map of Romwe Catchment (after Butterworth *et al.*, 1995)

The gneisses underlying the catchment range from dark coloured (melanocratic or mafic) types, rich in ferromagnesian minerals such as pyroxene, mica and amphibole, to much lighter coloured (leucocratic) gneisses composed mainly of feldspar and quartz. Between these two extremes are a range of types which grade imperceptibly from one to the other. The various types are interbanded at all scales from a few centimetres to several hundred metres, giving rise to a complex sequence. However, three major units within which one type of gneiss seems to dominate have been identified:

#### ***Quartzo-feldspathic granulites***

These outcrop in three main areas; as the steep hills that form the southern divide of the catchment; in the extensively faulted and fractured region of the synform closure; and as a narrow band roughly tracing the line of the stream bed, which acts a barrier to lateral groundwater flow. The generally resistant nature of this unit is the reason for it occupying the higher ground in the catchment. The granulites are dominated by quartz and potassic feldspar which together account for 90% of the rock.

#### ***Leucocratic pyroxene gneisses***

This unit consists of a series of leucocratic pyroxene gneisses banded together with subordinate amounts of quartzo-feldspathic gneisses. The unit outcrops within the core of the synform and in the gently sloping strip of land between the foot of the southern hills and the stream bed. Within this unit pyroxene is usually the dominant mafic mineral though occasionally amphiboles or biotite may be more abundant. These mafic minerals constitute 25% of the rock.

#### ***Pyroxene gneiss***

The pyroxene gneisses outcrop in the lower lying parts of the catchment. These areas include a narrow outcrop extending along the northern bank of the stream and a low lying arcuate region wrapped around the closure of the synform. Hypersthene (a pyroxene) is the dominant mafic mineral, often forming up to 70% of the rock. The high concentration of mafic minerals means that these rocks are less resistant to weathering than the quartz-rich granulites. The pyroxene gneisses weather to a deep red, iron-rich, loamy sand with some patchy development of a ferrocrete layer.

### **4.1.5 Soils**

Three soil types are found within the catchment (Butterworth *et al.*, 1995). The variations in soil type are mainly due to the difference in the parent rock.

On the southern side of the stream, light grey coloured, sandy soils occur where the leucocratic gneisses are found; these are kaolinitic, fersiallitic soils. The coarse textured surface horizons are dominated by a fine to medium-grained sand fraction. These soils have poor water-holding capacity. In many locations these are underlain by thick clay at depths of between approximately 0.3 and 1.5 m.

On the northern side of the stream kaolinitic, fersiallitic, red clays derived from the more mafic gneisses dominate. These soils are more fertile, with good physical properties; in areas of Zimbabwe underlain by basement rock, these are the most important soils for crop production.

The third and least extensive soil type are vertisols which occur as the lower members of the catenal sequence. These are found in small patches on the north of the stream near the centre of the catchment.

### **4.1.6 Land use**

Approximately 38% of the land is cultivated, cropping being restricted to the valley bottom land with its gentle slopes and deep soils (Butterworth *et al.*, 1995). Maize is the most important crop in the catchment, followed by groundnuts and cotton. These are grown as rainfed crops, planted following the start of the rains

(November to January) and harvested approximately 4 months later (March to May). Throughout the year irrigated garden vegetables are grown, including onions, tomatoes and leaf vegetables. These are an important source of nutrition, particularly during the dry season, when other food sources are scarce.

The remaining 62% of the land is under natural vegetation. Miombo woodland is the main vegetation type; it is found on the rocky hillslopes and accounts for 55% of the catchment area.

## 4.2 Groundwater abstraction

### 4.2.1 *Water use*

The majority of water used in the catchment is abstracted from wells. Some surface water may be used for livestock and for washing during the wet season but this is a small fraction of the total. Water is needed for domestic use ie. drinking and washing, for irrigation of vegetables, for the making of bricks and for livestock. Abstraction from wells is variable, some are rarely used others can support over 30 people and a garden. The amount of water abstracted from a well depends on many factors: how many people rely on it; the distance from the users; the method of abstraction; whether the well has an associated garden; the quality of the water; and the well performance.

In the Romwe catchment the collector well has changed the pattern of abstraction from traditional wells. It is estimated that the amount of water abstracted from the collector well is greater than the sum of the abstraction from all other wells. This is not solely due to the irrigation of the collector well garden, as many local people use the collector well for domestic water. It provides cleaner water than most unprotected traditional wells. This may have reduced the amount of water abstracted from the traditional wells.

### 4.2.2 *Well Survey*

In 1993 a survey was carried out of all the wells in the catchment, as well as some just outside of the catchment. The wells were numbered and a database was created containing information on each. The location of all of the wells is given in Figure 4.4. In general, wells are located near to stream channels and/or close to the owner's house or garden. The number of wells in the catchment has increased dramatically since the 1960s (Figure 4.5). The rate of increase was greatest during the 1980s and early 1990s, the period of reduced recharge which culminated in the drought of 1991/92 (Price, 1993).

There are a total of 26 traditional dugwells presently operational within the surface water catchment and 5 just outside. In addition to these there is: the collector well; one deep borehole with a handpump; and one shallow 6" borehole which is not used as a pump has not been fitted. The traditional wells range in depth from 3.60 m to 13.69 m, with an average of 9.11 m and the diameter ranges from 0.70 m to 2.00 m, with an average of 1.04 m. Only three of the wells are not lined. Stone and/or brick is used mostly and concrete sometimes. Thirteen are lined to the base, six are lined approximately half way and nine have just the top few metres lined. A few of the wells have a history of collapsing, these tend to have been shallow to begin with, mainly in the centre of the valley near the stream bed. This may be due to the greater thickness of unconsolidated material.

During dry years when wells dry-up they may be deepened. Deepening will proceed as long as the formation is weathered enough to allow it to be broken-up using hand tools. When the well reaches bedrock it is unlikely that any further digging can take place and so those wells which have reached the bedrock are at their maximum depth. This is the case in nine of the nineteen wells in the catchment from which information on rock type at the base could be obtained.

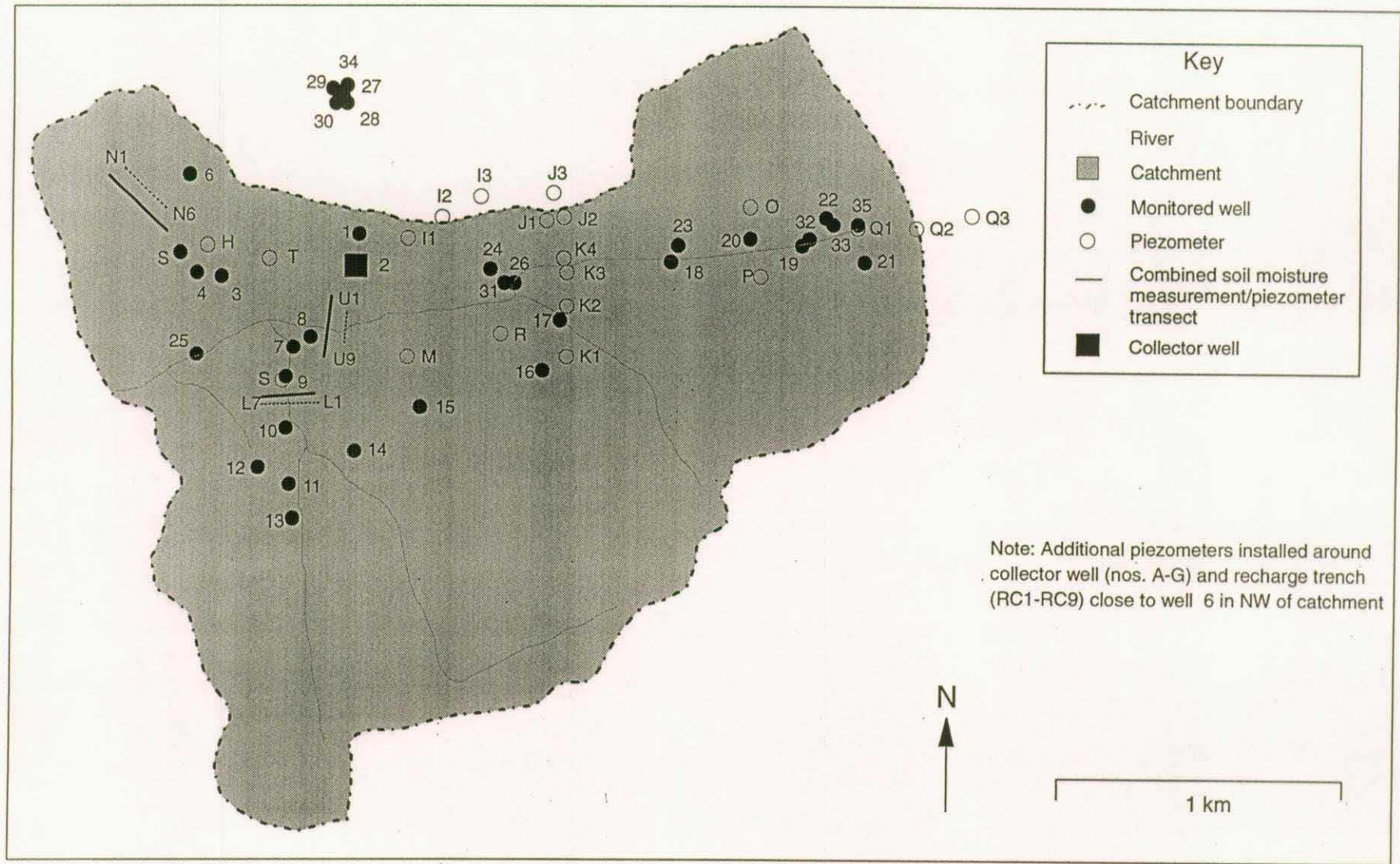


Figure 4.4 Locations of wells and piezometers in Romwe Catchment with identification numbers (after Butterworth *et al.*, 1995)

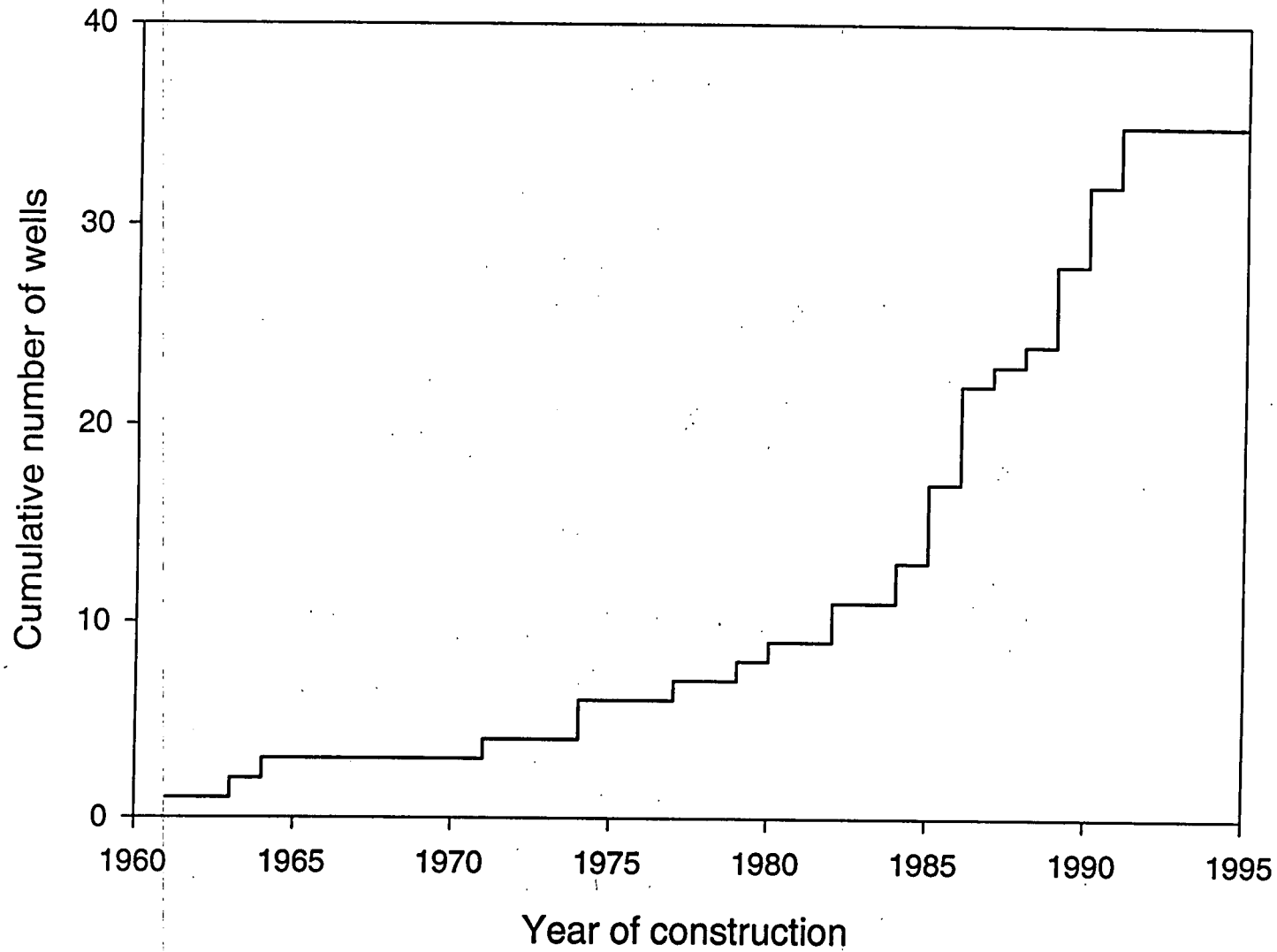


Figure 4.5 Cumulative number of wells in Romwe catchment since 1960



Price (1993) reports that half the wells ran dry during the drought of 1991/92. Two of the most productive wells in the catchment had to be deepened. The two relatively high rainfall periods following replenished the aquifer to a certain extent but prior to the late rains of the wet season of 1994/95 many wells had again dried-up.

Within the period of the project there was a degree of spatial correlation observed in the wells which run dry. Those wells in the north-west of the catchment are least likely to run dry, they are also the most productive wells. The wells which are located along the stream bed are shallower and though the water-level is also nearer to the surface they have a greater tendency to dry-up. The wells on the southern side of the catchment are also more likely to dry-up although the average depth here (10.59 m) is greater than the overall average for the catchment.

#### 4.2.3 *Water-level monitoring*

To allow the well responses to abstraction to be analysed the water-levels in the wells listed in the database have been monitored weekly in most cases since late 1992. The well water-level is measured in the morning before any abstraction has taken place. From late 1993 the frequency increased to daily after a rainfall event. The water-level monitoring round also includes a series of piezometers. The positioning of these piezometers will be discussed in section 4.3. A proportion were constructed to allow the depth of the water-table in the locality of some wells to be measured and compared with well water-levels.

It is difficult to analyse well water-levels when daily abstraction is not constant. However, monitoring in 1993/94 indicated that the upturn in well water-levels at the end of the dry season was at approximately the same time (within a few days) across the whole catchment. In contrast, the magnitude of the rise to maximum water-level, the time to reach the maximum and the rate at which the water-levels recessed, varied greatly.

The well water-level responses both to aquifer recharge and abstraction show some spatial correlation which it is thought relates in part to the underlying geology. In the discussion of the water-level fluctuations a sample of typical wells have been grouped according to their location (Figures 4.6a-g). At the time of analysis a full set of well and piezometer water-level data was only available for the season 1993/94.

Wells 1, 3 and 6 show a water-level fluctuation characteristic of those in the north and north-west of the catchment. The water-level rise for the initial period of the wet season of 1993/94 was at a rate of approximately 5 cm/day. This rate was much less than elsewhere in the catchment. The magnitude of the rise was also smaller than in other areas. For 1993/94 this was on average 4 m. The time taken to reach the maximum was very similar for all wells in this area, on average 80 days. This was the case both for little used wells and those with significant abstraction.

Wells 10, 12, 17 and 22 show responses characteristic of the southern side and eastern end of the catchment. Here the water-level rise is much greater than on the northern side. The rise seen in well 10 in 1993/94 is quite dramatic: 12 m in 23 days. This rise was primarily in response to the large storm of 97 mm on 27 November 1993. The water-level in the well holds-up for a period of approximately 100 days, but then begins to fall rapidly and within another 190 days the well is virtually dry. The spike in the water-level seen on the recession is due to a late rainfall event. These spikes can be seen elsewhere on the water-level plot.

Wells 12, 17 and 22 show a response to rainfall similar to that of well 10, though the magnitude and rate of the water-level rise is not so great. The water-levels in these wells also fall rapidly from their maximum. In general, the water-level recession in the wells on the southern side and the eastern end of the catchment is varied, but significantly two-thirds run dry by the end of the dry season. This statistic includes those wells which have a water-level which is kept within a few tens of centimetres of the base of the well by the owner

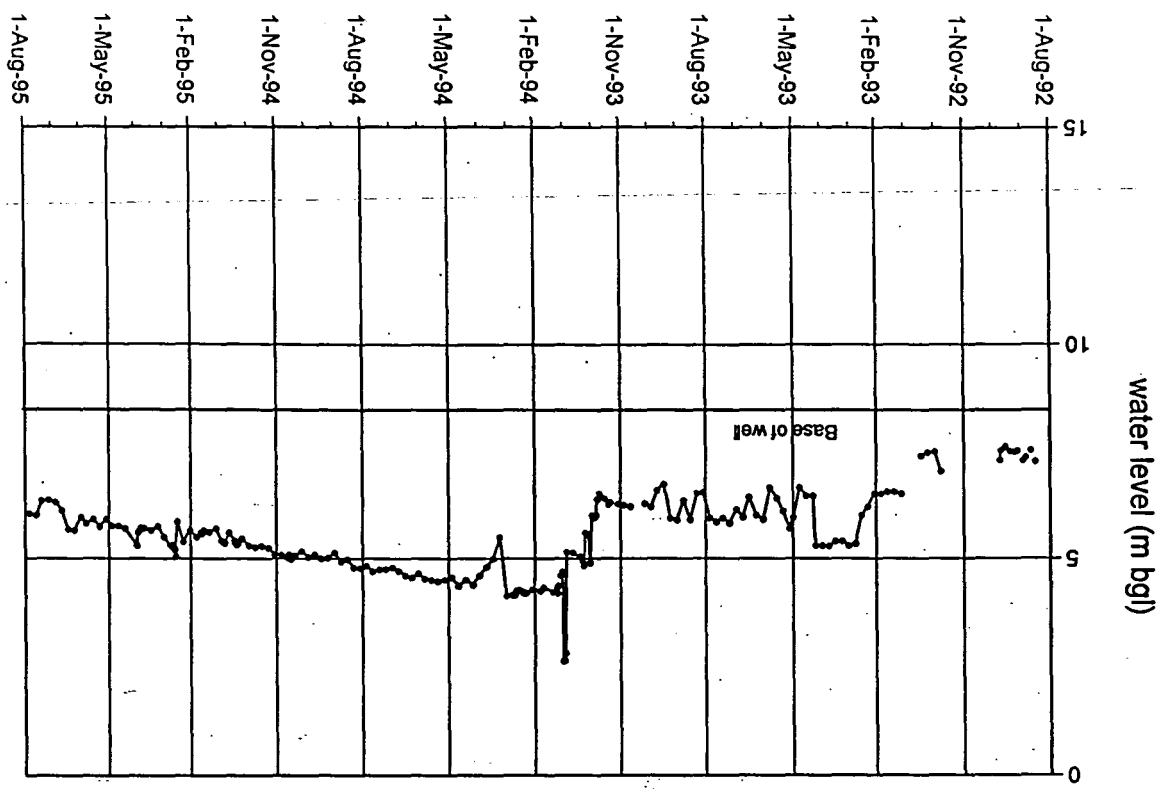


Figure 4.6b Depth to water, start of monitoring to August 1995: Well 3, Romwe Catchment

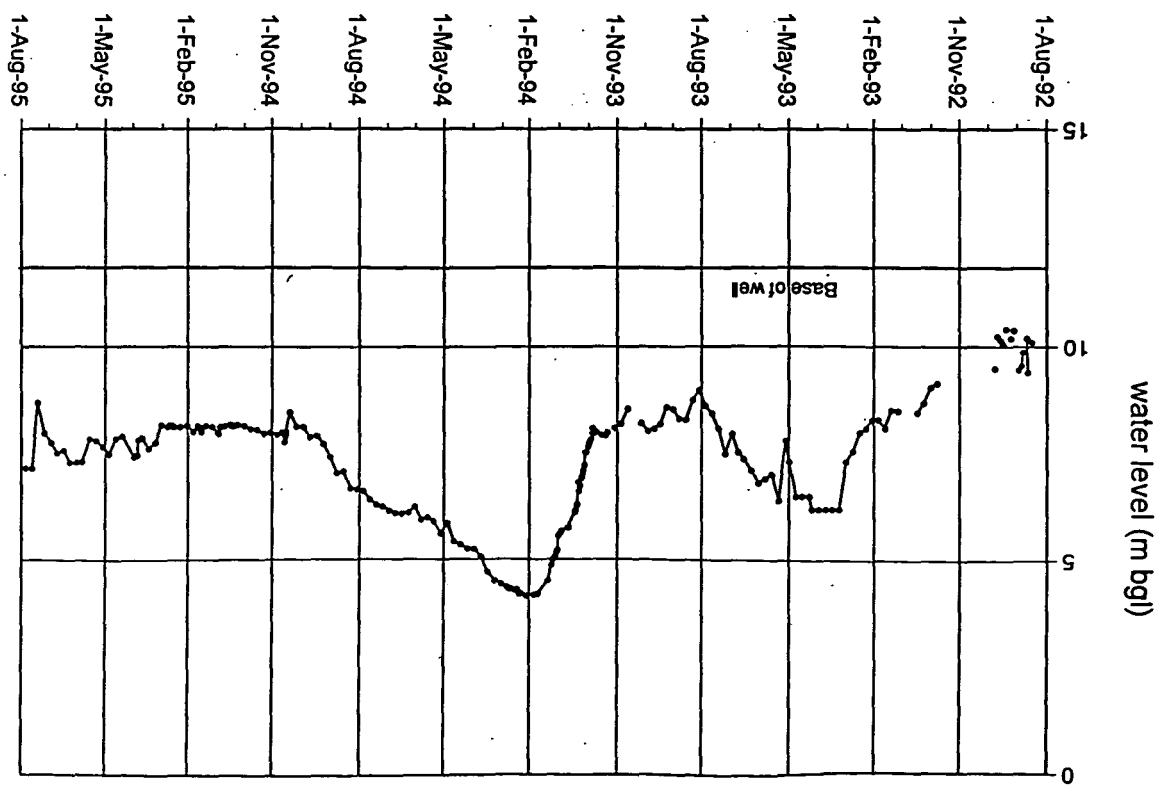


Figure 4.6a Depth to water, start of monitoring to August 1995: Well 1, Romwe Catchment

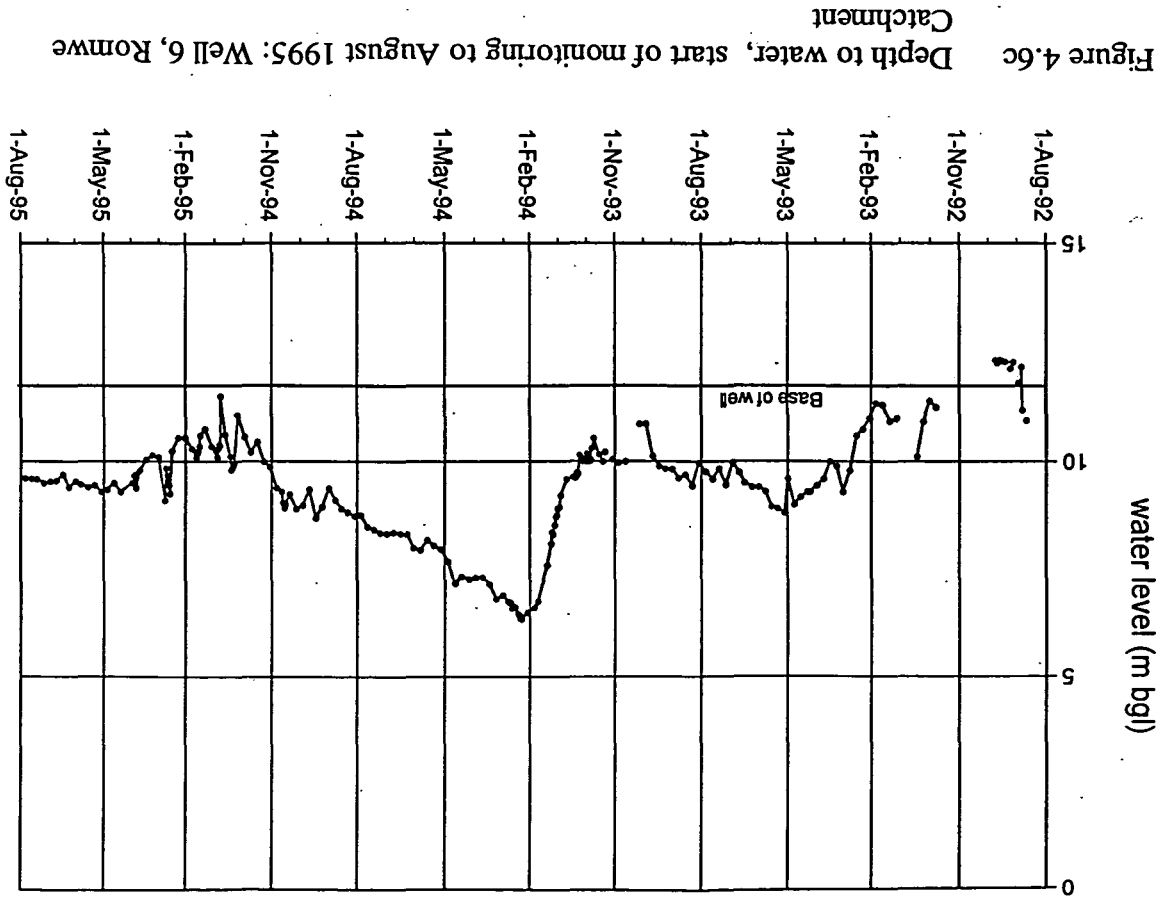
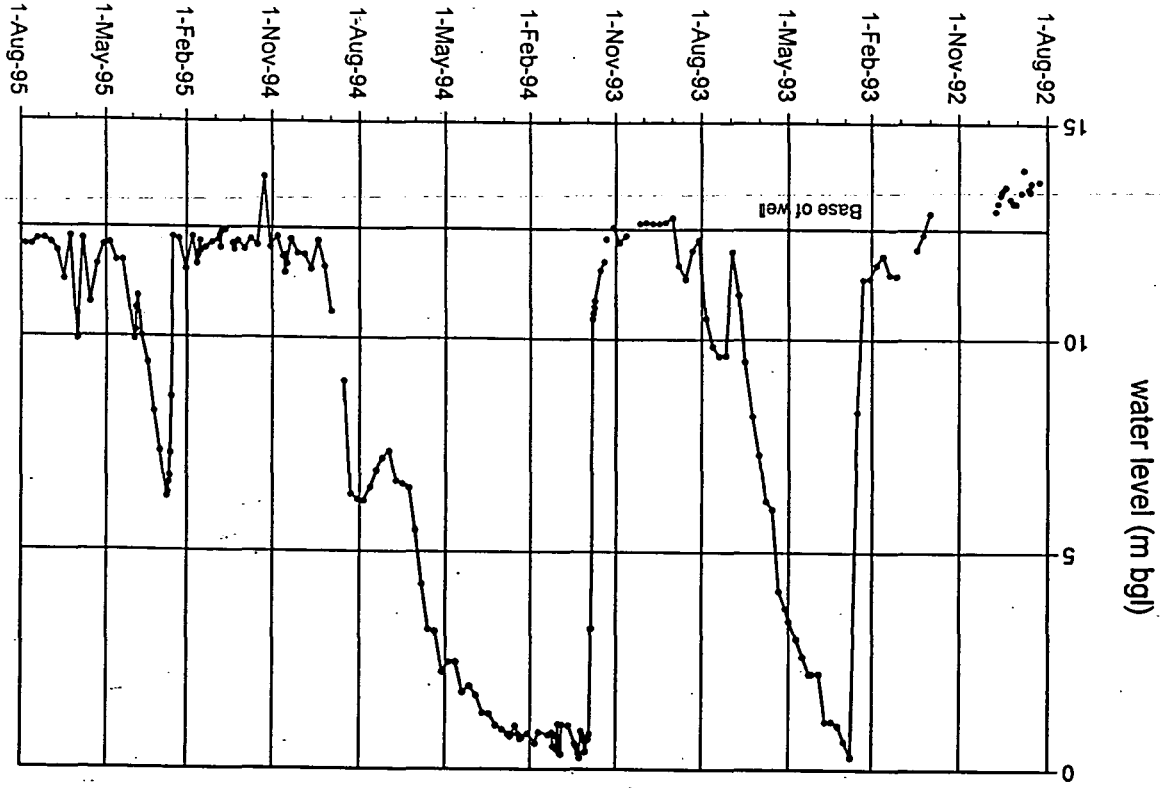


Figure 4.6d Depth to water, start of monitoring to August 1995: Well 10, Romwe Catchment

Figure 4.6c Depth to water, start of monitoring to August 1995: Well 6, Romwe Catchment

Figure 4.6f Depth to water, start of monitoring to August 1995: Well 17, Romwe Catchment

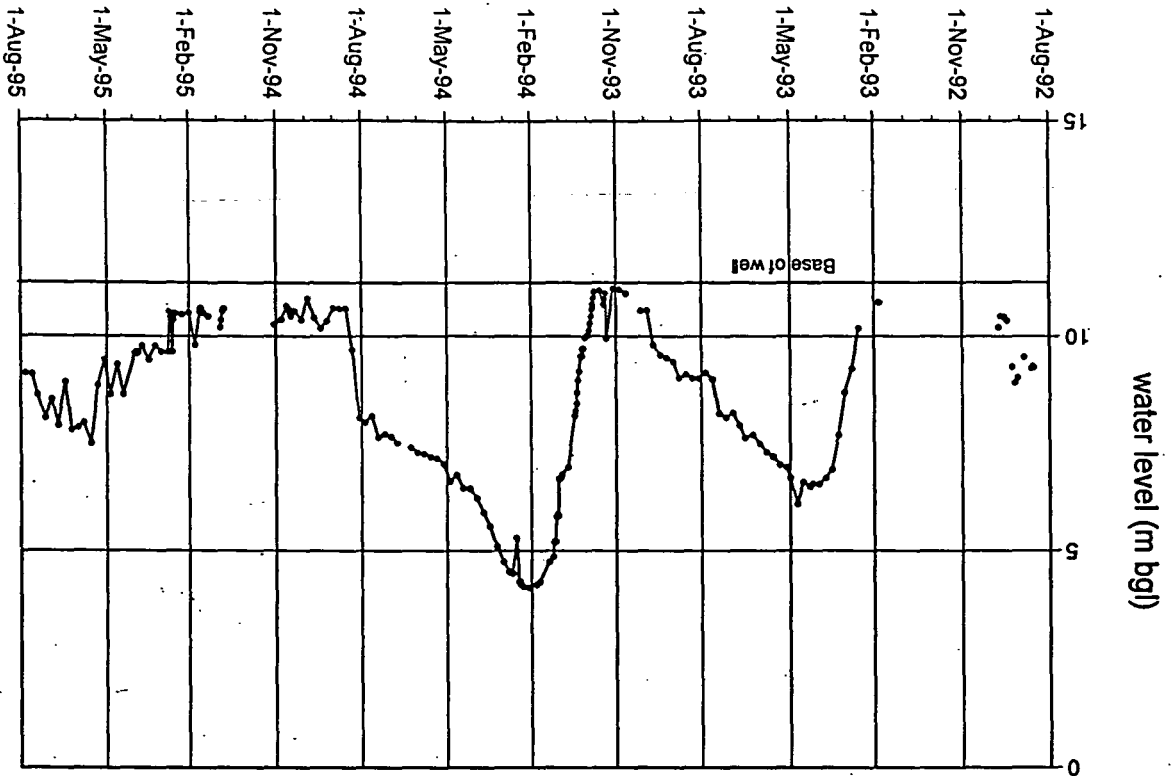
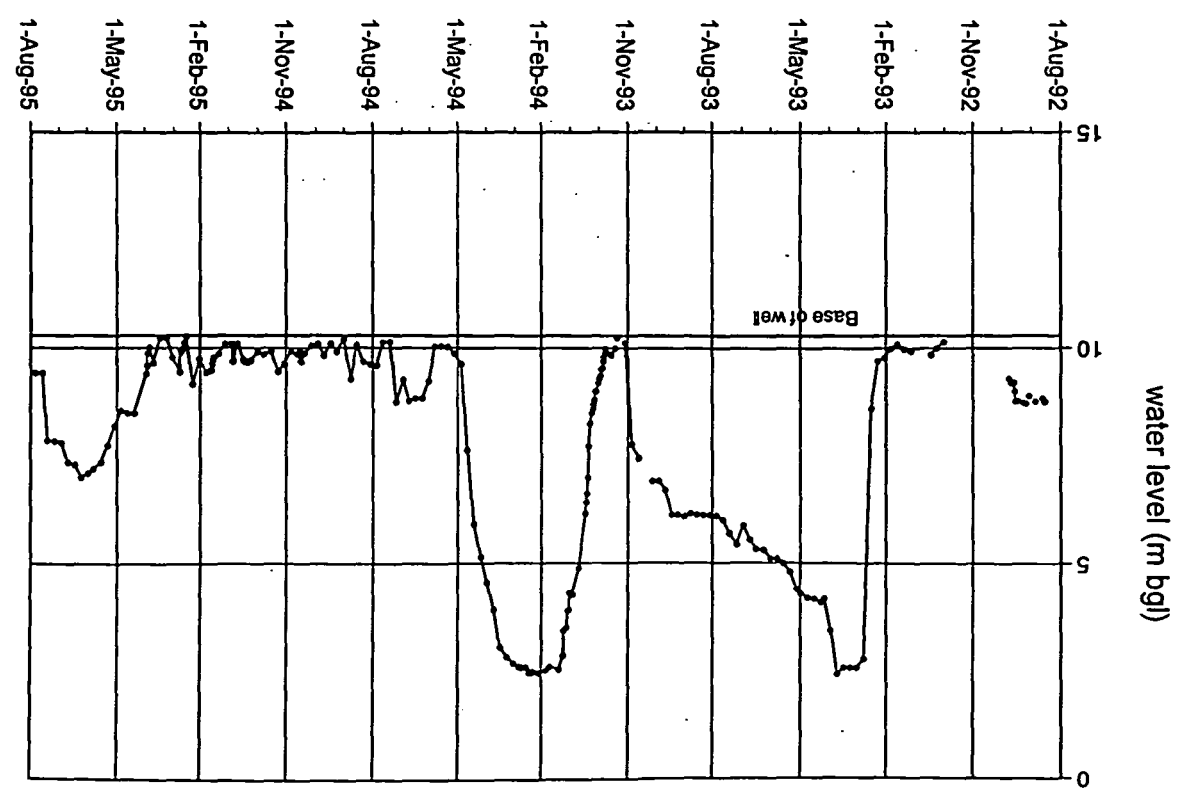
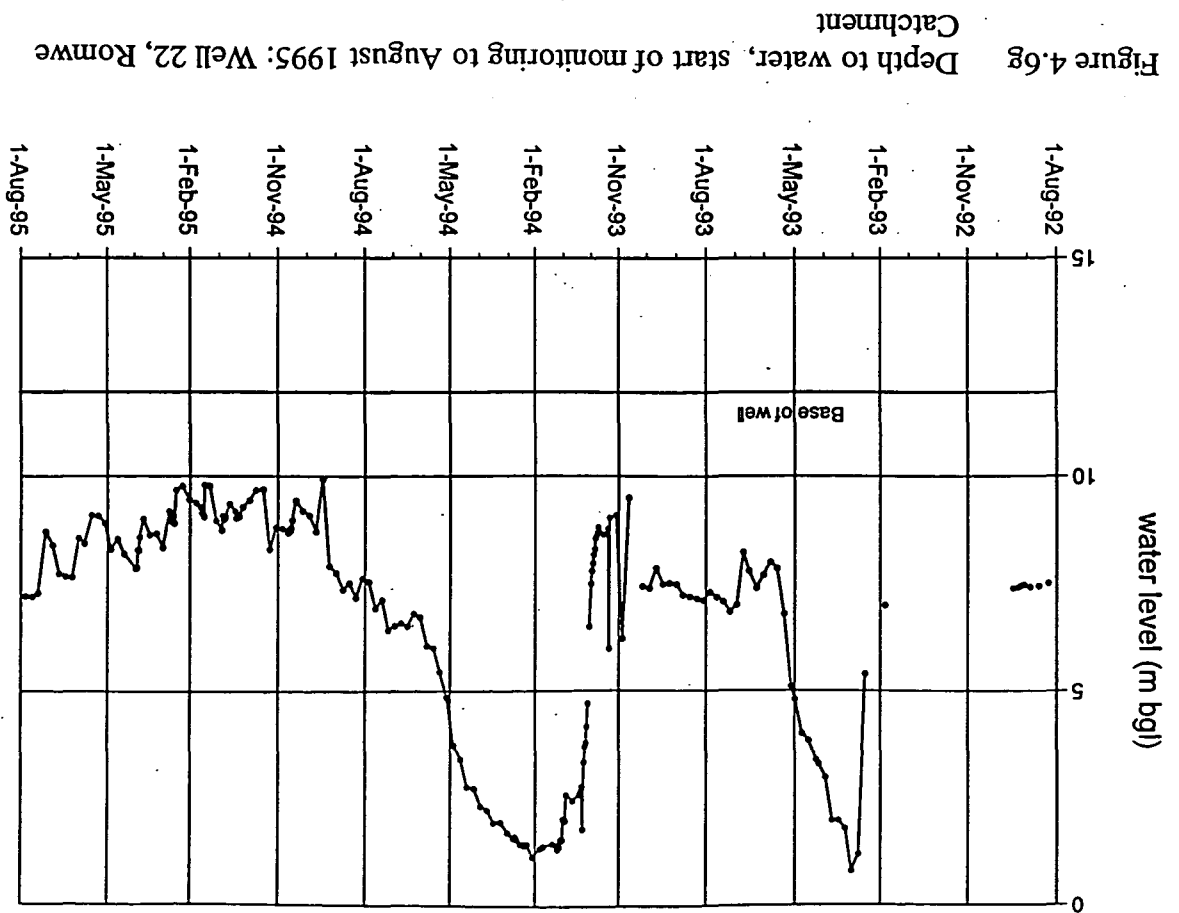


Figure 4.6e Depth to water, start of monitoring to August 1995: Well 12, Romwe Catchment





by greatly reducing abstraction. This ensures a supply of domestic water is retained but limits the irrigation of garden vegetables.

Though in 1993/94 the shapes of the well water-level plots differ across the catchment the first significant fall in the water-level is picked-up at approximately the same time in all the wells. This coincides with the last significant rainstorm of early 1994.

#### 4.2.4 Detailed well surveys

It is expected that a component of the fluctuation of water-levels in the wells in the catchment depends in varying degrees on the volume of water that has been abstracted. To obtain a better understanding of the well water-level responses to abstraction, more detailed studies were undertaken on five wells (1,6,10,17 and 22). The abstraction from the wells was monitored and short-term pumping-tests were carried-out. The wells were chosen as typical of those in the catchment, taking into account the well response and what was known of the level of abstraction prior to initiating the monitoring. The willingness of the owner to participate was also extremely important as it was they who monitored their daily abstraction. The abstraction monitoring was carried out on a daily basis starting from June 1994. The length of the monitoring period has varied from well to well: for well 17 it stopped in November 1994, for wells 1 and 22 it stopped in January 1995, but for wells 6 and 10 it is still continuing. The positions of all these wells can be found on Figure 4.4.

Figure 4.7 shows the monthly abstraction volumes for the five wells for the period June 1994 to May 1995. A full years record is only available for wells 6 and 10; the monitoring of the other three wells broke down during the year. It is difficult to pick up trends in the data within one year, but the monitoring has shown how the levels of abstraction compare between wells. The abstraction from Well 6 is significantly greater than from the other wells.

Figures 4.8a-e show how the weekly water-level in the wells compare with the weekly abstraction totals. These show, in general, that the water-levels in wells 10, 17 and 22 are lowered more than in wells 1 and 6 in response to pumping even though the abstraction from wells 10, 17 and 22 is less. Large downward steps in the water-level occur following a greater than normal level of abstraction.

Insight into well response is obtained by comparing well water-levels with water-levels in the aquifer measured in piezometers located within a few tens of metres (Figures 4.8a-e). It is noticeable that the shape of the water-level plots for wells 1 and 6 match closely that of the 'regional water-level'. This is not the case in wells 10, 17 and 22. Here the water-level in the well falls far below that in the aquifer nearby. The cone of depression around these wells has developed more than with the wells on the northern side. This appears to be the case even though the abstraction from well 6 is much greater than can be achieved from the other wells.

#### *Pumping-tests*

The cause of the development of a steep cone of depression around a shallow well is the lower transmissivity and storativity of the formation within which it is located. To investigate the variation in aquifer properties pumping-tests were carried on each of the five selected wells. Testing is a difficult process to undertake on traditional wells in use. To ensure the test is valid the water-level must be allowed to recover to the regional water-level prior to the test. Once the test pumping has ceased the well must be left to recover preferably to within at least 75% of its starting level. The owners therefore had to refrain from using the well for a period of up to 5 days. This is a long time not to have access to the well. In each case an alternative source of water was used or supplied. To keep the time for the pumping test procedure as short as possible the test was limited to a period of pumping of on average 30 minutes. A pumping rate of 1 litre/second was used on all the wells.

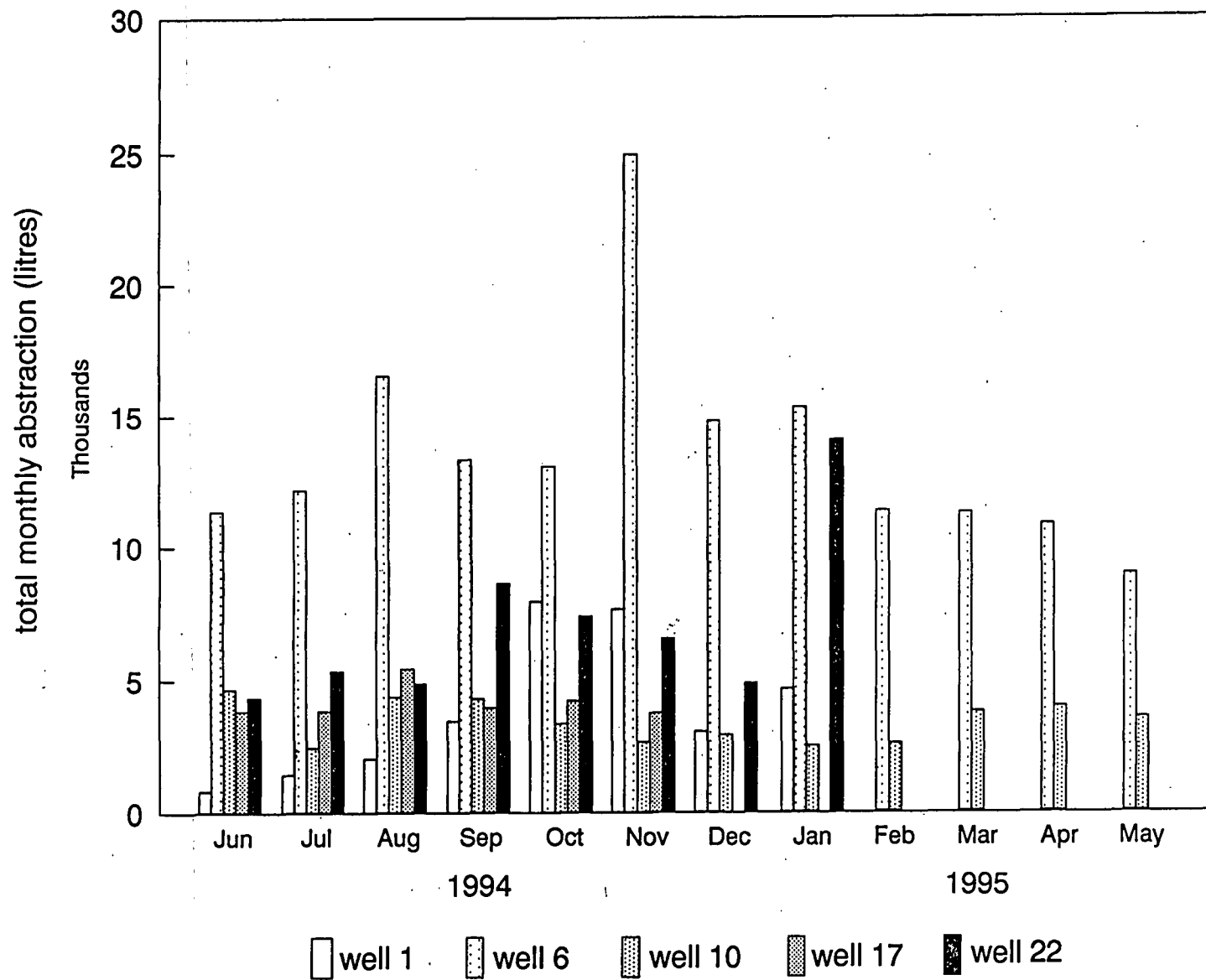


Figure 4.7 Comparison of monthly abstraction from five wells in Romwe Catchment

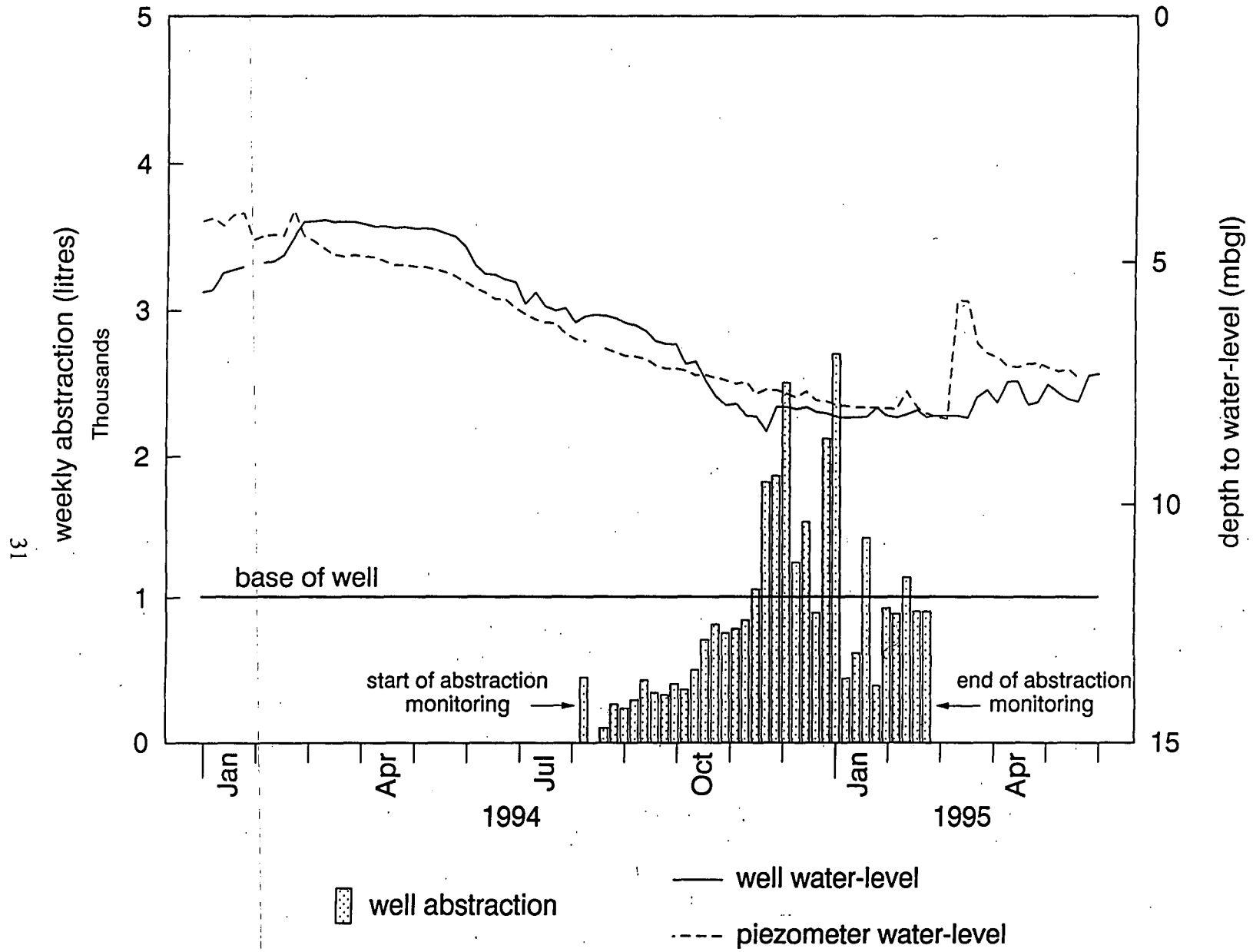


Figure 4.8a Comparison of well and piezometer water-levels and well abstraction in Well 1, Romwe Catchment



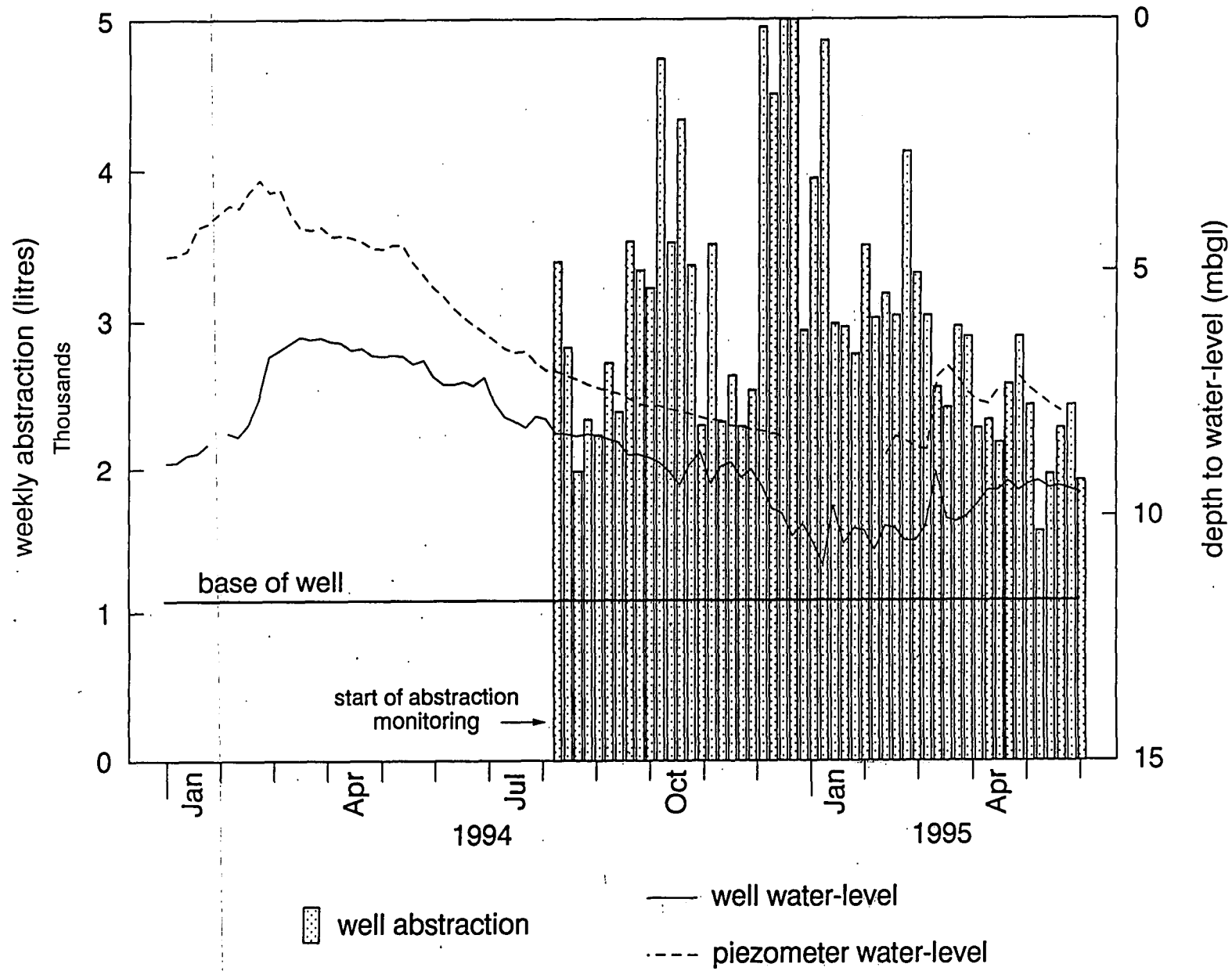


Figure 4.8b Comparison of well and piezometer water-levels and well abstraction in Well 6, Romwe Catchment

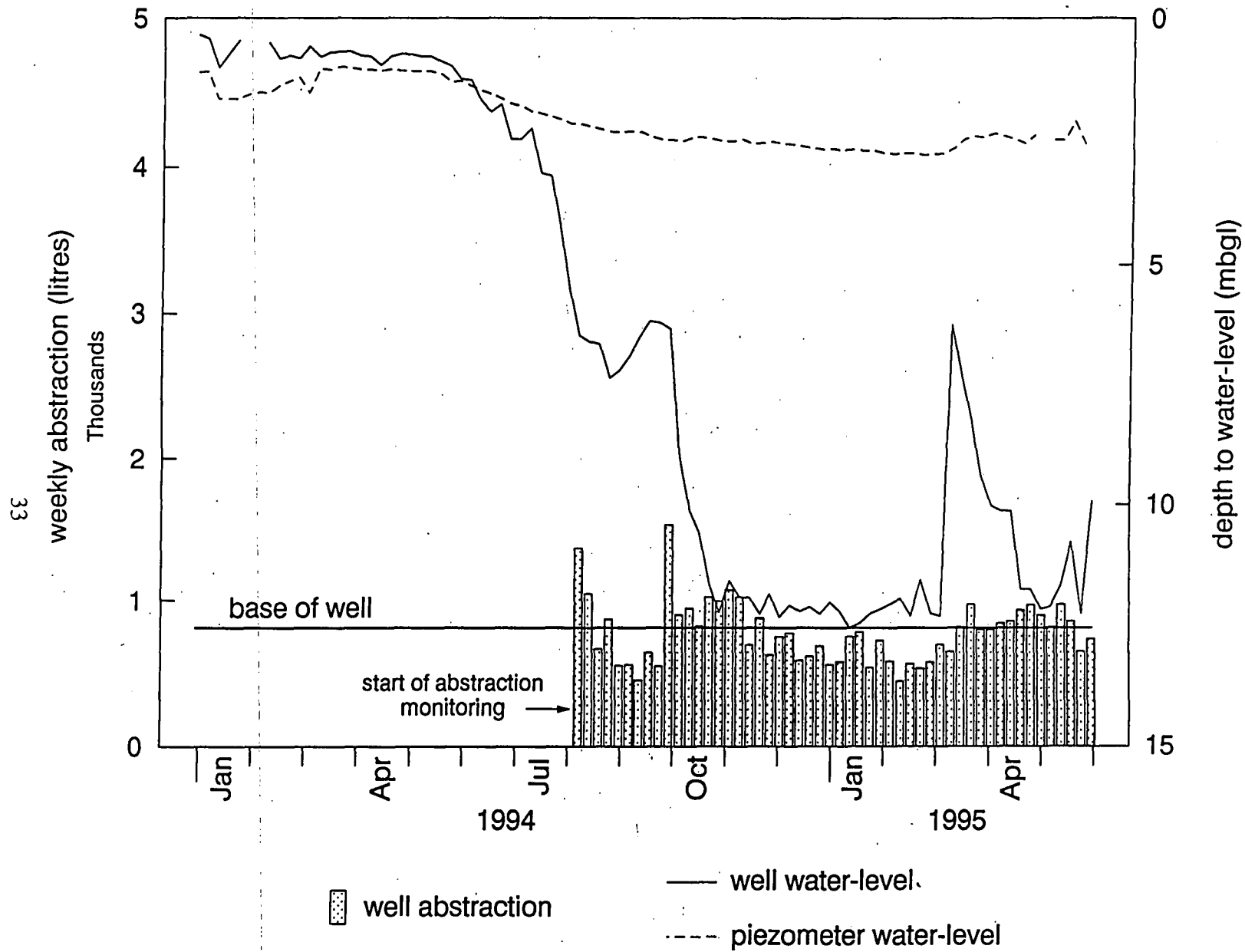


Figure 4.8c Comparison of well and piezometer water-levels and well abstraction in Well 10, Romwe Catchment

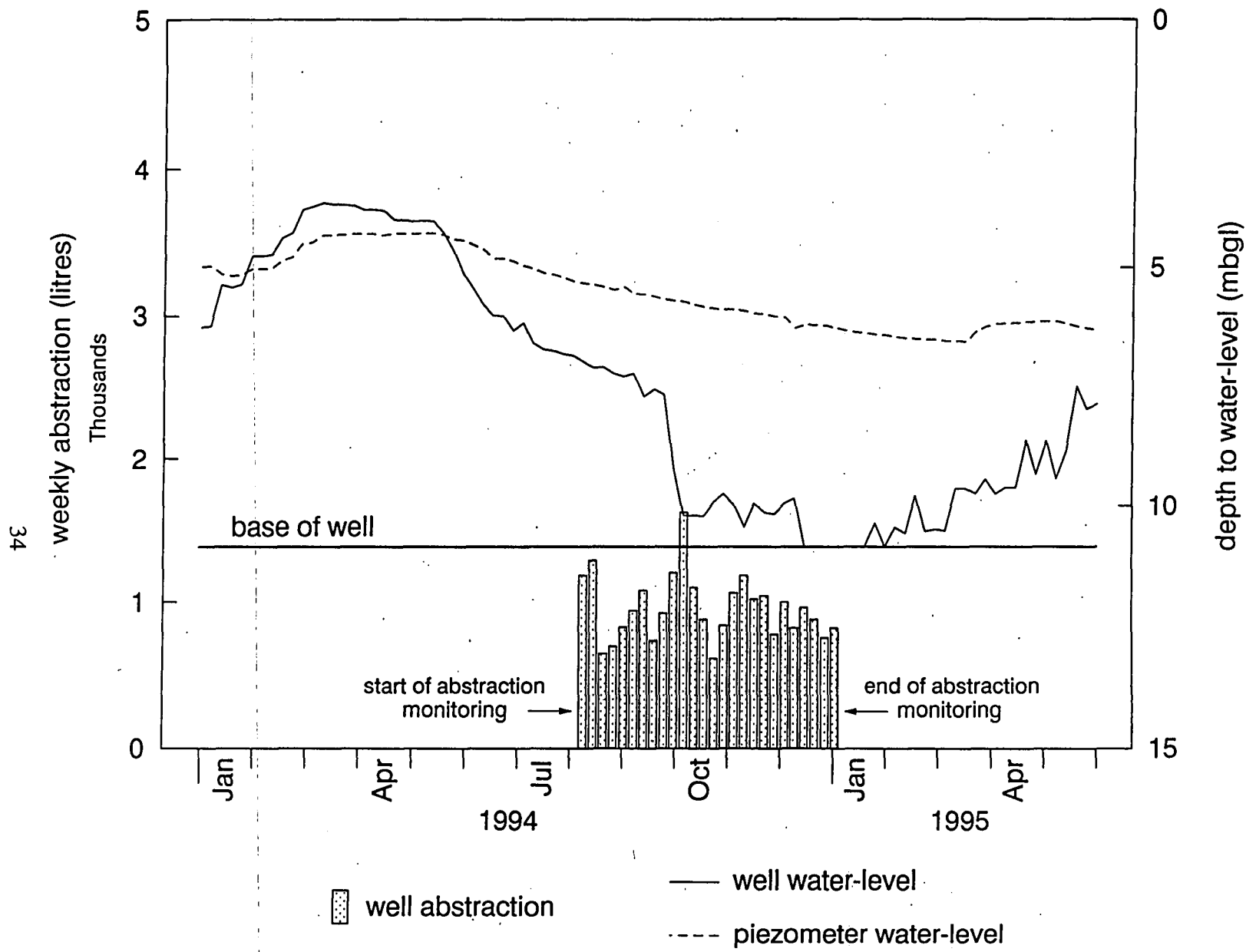


Figure 4.8d Comparison of well and piezometer water-levels and well abstraction in Well 17, Romwe Catchment

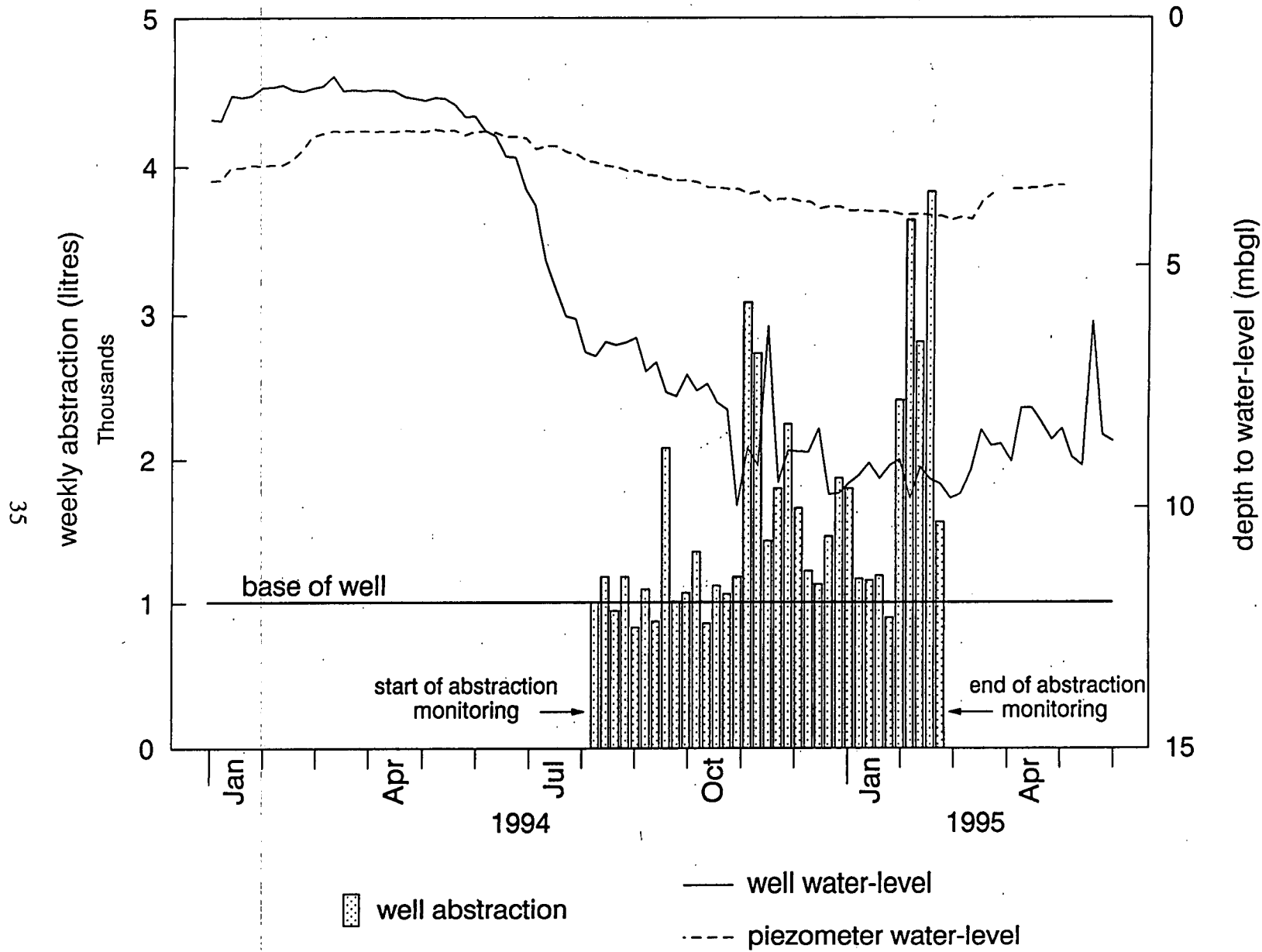


Figure 4.8e Comparison of well and piezometer water-levels and well abstraction in Well 22, Romwe Catchment

The analyses of the tests were carried out using the in-house BGS computer package BGSPT (Barker, 1989). This code will be described more fully in Chapter 5. It is an analytical model which in this case has been used to fit pumping-test data to a confined aquifer model. The results of the analyses are given in Table 4.1. The model allows the radius of the well to vary when fitting the pumping-test data. This variation enables well hydraulics and design characteristics that do not fit a simple conceptual model to be accounted for. In four out of the five analyses the radii suggested by the best fit are greater than the actual radius. This may be due to a network of fractures in the vicinity of the wells that increase their effective radii. Only in the case of well 17 is there any confidence given to the value of storativity obtained.

**Table 4.1 Results of pumping-tests on traditional wells in Romwe catchment**

Well no.	Actual radius (m)	Effective radius (m)	Transmissivity (m <sup>2</sup> /day)	Storativity
1	0.525	0.67	0.56	1.6 x 10 <sup>-5</sup>
6	0.4	0.74	1.99	1.15 x 10 <sup>-6</sup>
10	0.65	0.7	0.22	1.0 x 10 <sup>-3</sup>
17	0.5	0.5	0.25	1.1 x 10 <sup>-3</sup>
22	0.6	0.63	0.33	2.9 x 10 <sup>-5</sup>

The results confirm the inferences from the comparison of well and piezometer water-levels. The transmissivities estimated from wells 1 and 6 are relatively high and well 10 is the lowest. It is possible that the high value of transmissivity from the test on well 6 is due to local faulting or fracturing.

The BGSPT package as well as fitting pumping-tests, also has a module that allows the drawdown due to a specified pumping regime to be simulated. This module was used to validate the pumping-test results. The values of transmissivity and storativity obtained from the pumping-tests were input to this model along with an average value of daily abstraction obtained from the monitoring data. The resultant drawdown after a period comparable to that of the dry season was calculated. This drawdown in the case of wells 1 and 6 gave a reasonable fit to the drawdown seen in the well, having allowed for a natural regional water-level recession. This was not the case for wells 10, 17 and 22. Although the simulated drawdown was greater in these three relative to wells 1 and 6, it was not as large as that shown by the monitoring data. The drawdown experienced in reality will most likely be greater due to the development of a seepage face in the well. This occurs in most pumping wells but more so in those situated in aquifers of low transmissivity and storativity.

The results from this detailed study have shown that even within a small area, well performance can be quite varied. This variation in performance may correlate with the underlying geology. This hypothesis will be developed in section 4.3.

#### 4.2.5 Collector well

Using the data collected from the five wells, a value for the total abstraction from all the traditional wells in the catchment over the period of a year was estimated at 2000 m<sup>3</sup>. This compares with a value of approximately 2500 m<sup>3</sup> for the collector well. It is significant, however, that the total yearly abstraction (4500 m<sup>3</sup>) when spread over the whole catchment is equivalent to only 1 mm of recharge.

The collector well has obviously had a dramatic effect on the abstraction within the catchment since it was constructed in 1991. The collector well is preferred by many as a source of drinking water as it has less suspended sediment than most of the traditional wells. It is also one of only two communal wells in the catchment fitted with a hand pump.

A comparison of the collector well with a nearby traditional well (well 1) of the same depth (Figure 4.9) shows how the larger diameter of the collector well and its laterals have resulted in a smaller comparative drawdown for a substantially larger abstraction rate. Pumping-tests carried out on the collector well before and after laterals were drilled will be presented and discussed in chapter 5. A cross-section of water-levels in the collector well, nearby traditional well (well 1) and a number of piezometers is given in Figure 4.10. The section shows how the laterals have extended the radius of influence of the well, keeping the cone of depression shallow and the drawdown in the well low.

### 4.3 Groundwater recharge processes

The previous section discussed the water-level fluctuation in the catchment wells. This section will take the analysis further and integrate it into a study of the recharge processes taking place in the catchment as a whole.

#### 4.3.1 Catchment instrumentation and monitoring

Instrumentation has been installed in the catchment by both BGS and IH to investigate the controls on groundwater recharge and movement. In addition, IH are undertaking water balance studies on the catchment as a whole and on sub-catchments considered representative of the region i.e. cropped areas with different soil types and a woodland area on the hillslopes. This sub-section summarises the catchment instrumentation and monitoring; for a full description see Butterworth *et al.* (1995).

#### *Piezometers*

In 1993 a series of piezometers were drilled across the catchment. The location of these piezometers can be seen on Figure 4.4. The criteria for locating these holes were as follows:

- to monitor near-well water-levels
- to monitor regional water-levels
- to position groundwater divides
- to investigate areas of possible localised recharge
- to identify head differences between the shallow and deep aquifers

The piezometers were drilled initially with drag bits until the formation material became too hard, and then with the down-the-hole hammer technique. Logs were kept of the drill-time for each rod and the material being drilled. The piezometers are 0.1 m in diameter, open holed but with plastic slotted screen to ensure access for a water-level dipper. They were completed at the surface with metal casing and covered with a metal cap secured by a bolt. The majority of piezometers were drilled through the shallow weathered layer of the rock and 0.5 m into the bedrock, though some piezometers were drilled deeper into the bedrock. The piezometers range from 1.5 m to 29.3 m in depth. Monitoring of the water-levels was carried out on the same basis as the well monitoring.

#### *Rainfall and other meteorological measurements*

As mentioned in Section 4.1, reliable rainfall measurements have been taken in the catchment since November 1993 when a network of 10 raingauges was installed. This network will allow the spatial variation in rainfall to be analysed (Butterworth *et al.*, 1995). In addition to rainfall quantities, chloride ion

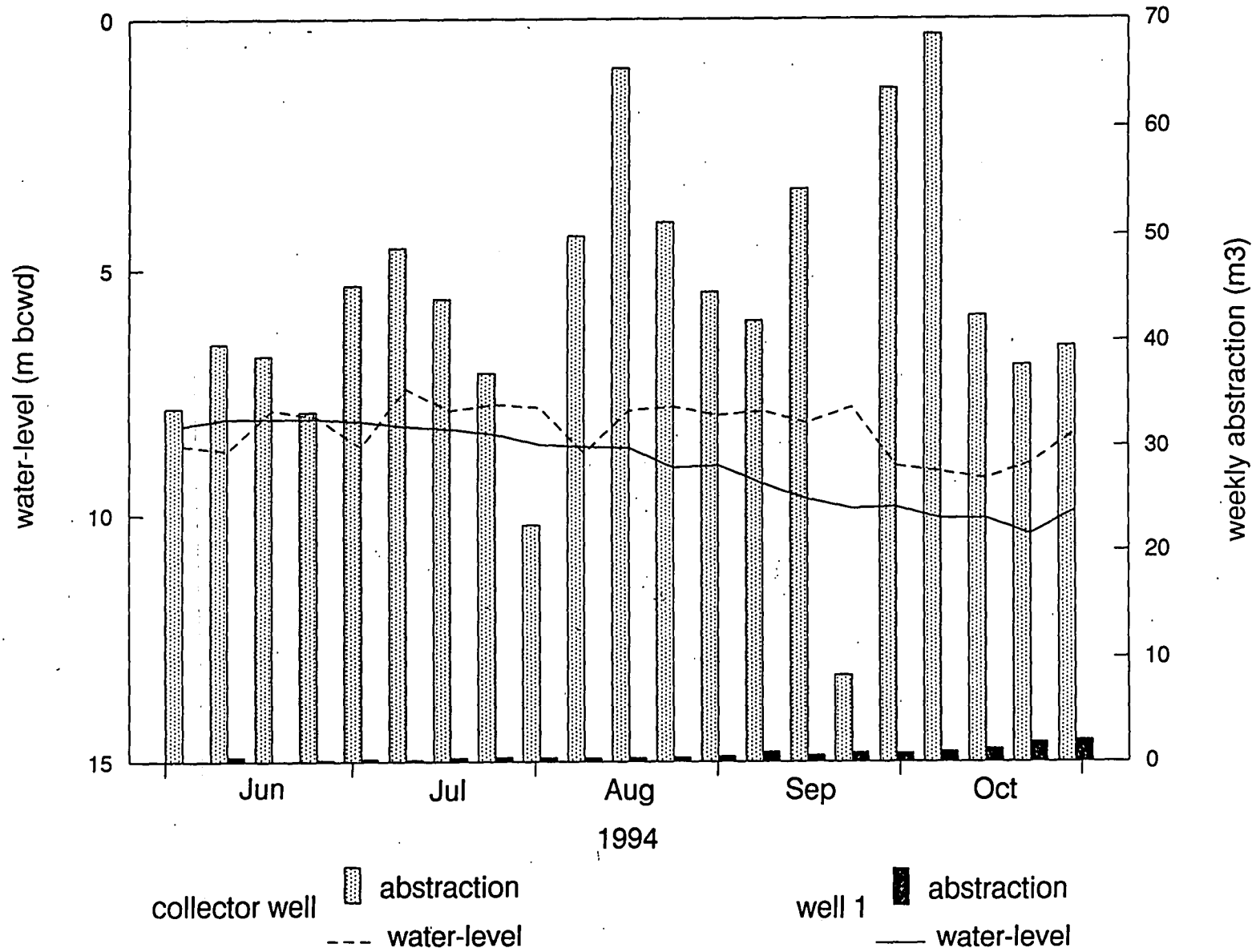


Figure 4.9 Comparison of well water-levels and abstraction from collector well and well 1

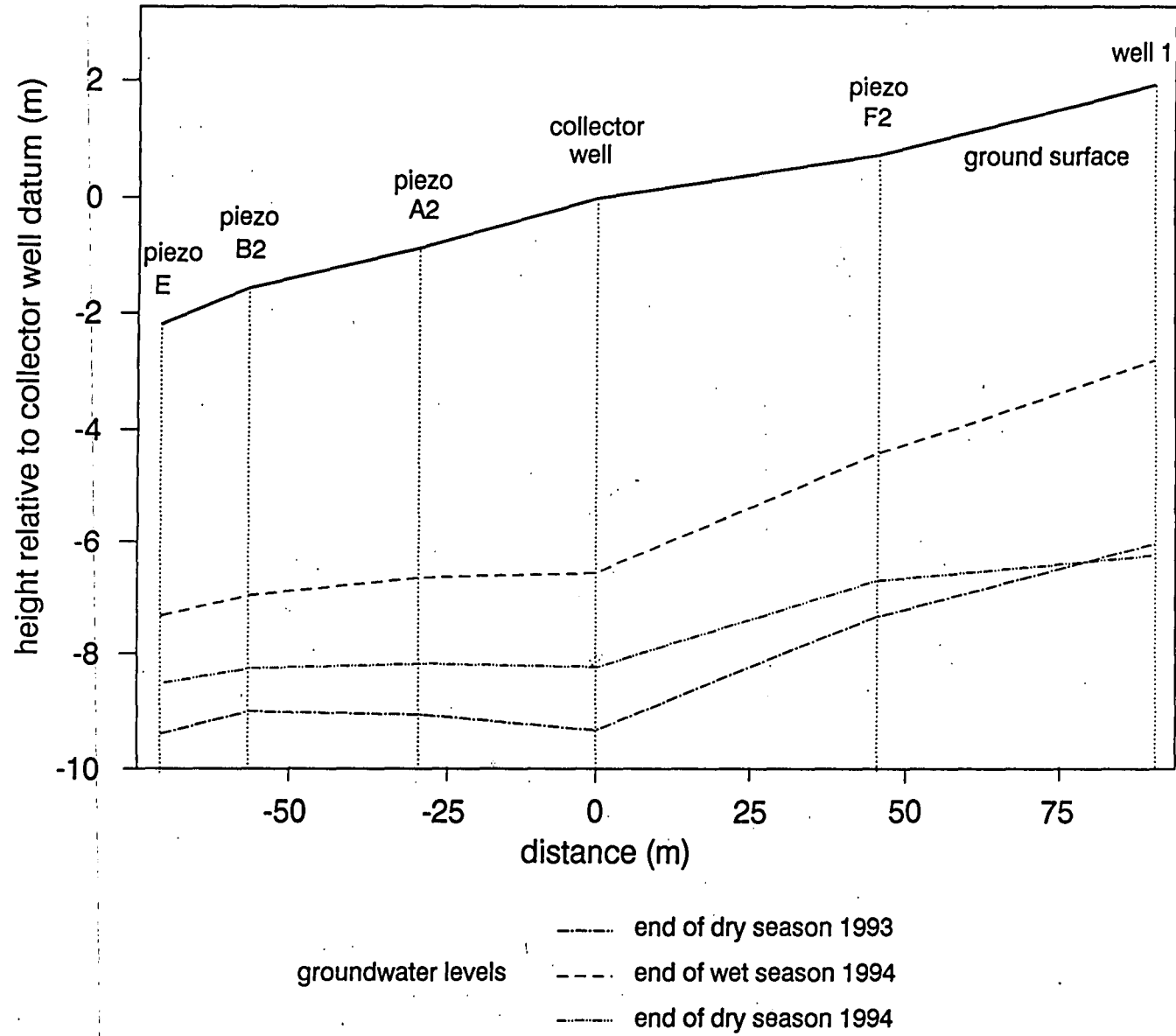


Figure 4.10 Cross-section showing the water-levels in the vicinity of the collector well, 1993/94



concentrations are being measured. The chloride data have been included, along with groundwater chloride concentrations, in a chloride flux balance that will be discussed later in this report. Since 1994 an automatic weather station has been operational in the catchment. This has allowed potential evaporation to be calculated.

#### ***Water balance studies***

Water balance studies are being undertaken at three different scales; plot, sub-catchment and catchment scale (Butterworth *et al.*, 1995). Within these the intensity and methods of measuring water balance components vary.

Fourteen plots of 10 m by 10 m, located across the catchment on different soil types, have neutron probe access tubes installed to at least a depth of 1 m, to allow soil moisture to be measured.

Three sub-catchments have been established within the catchment. The woodland sub-catchment, with an area of 0.5 km<sup>2</sup>, is located in the hills on the southern side of the valley. Two cropped sub-catchments have been set-up, one on the red soil and one on the grey soil, each approximately 0.02 km<sup>2</sup> in area. These sub-catchments are managed by the farmers with limited supervision. Monitoring installations within the cropped sub-catchments include: a grid of neutron probe access tubes; mercury tensiometers to monitor soil movement; a large number of micro lysimeters to measure spatial variability in soil evaporation; and a 6 metre long trench into the clay horizon below the grey soils to measure interflow. Runoff gauging stations have been constructed at the outlets of all three sub-catchments, as well as at the outlet of the catchment as a whole.

#### ***Groundwater chemistry***

In March 1994 a groundwater sampling round was undertaken. Samples were obtained from all wells and the majority of piezometers. These samples were analysed for all major ions, as well as trace elements. The sampling round was undertaken to obtain the groundwater chloride data as well as to provide a baseline groundwater chemistry.

#### ***Artificial recharge***

An artificial recharge trench was constructed in the catchment in 1993. The trench which is 15 m x 1.5 m and 1.5 m deep has three 6" boreholes drilled from its base into the bedrock. Initial analysis of this installation and the water-level in the associated monitoring piezometers does not show it to have any significant effect. Full analysis will be detailed in Macdonald and Thompson (in preparation).

#### ***4.3.2 Piezometer water-level analysis***

Monitoring of the majority of the piezometers in the catchment began in 1993. The water-level fluctuations for the wet season 1993/94 are analysed in the following sections. A number of representative water-level plots taken from the catchment are given in Figures 4.11 a-f.

#### ***Timing of a sustained rise in water-level***

Water-level data were analysed to obtain the first day of a sustained rise in water-level in response to rainfall. The vast majority of the upturns in water-level (79%) occurred within a four day period. The first day of this period was 24 November though it is likely that water-levels may have subsequently declined had a major rainfall event of 97 mm not occurred on 27 November.

#### ***Depth to water-level and magnitude of groundwater rise***

Analysis of the depth to the minimum water-level shows a wide spread from 12.53 m below ground-level in N5 to as little as 2.03 m in M. Overall the expected correlation of greater depth to water-level with increasing topographical height is observed. Although the depth to water-level increases in general with the distance

Figure 4.11b Depth to groundwater, start of monitoring to August 1995: Piezometer L7, Romwe Catchment

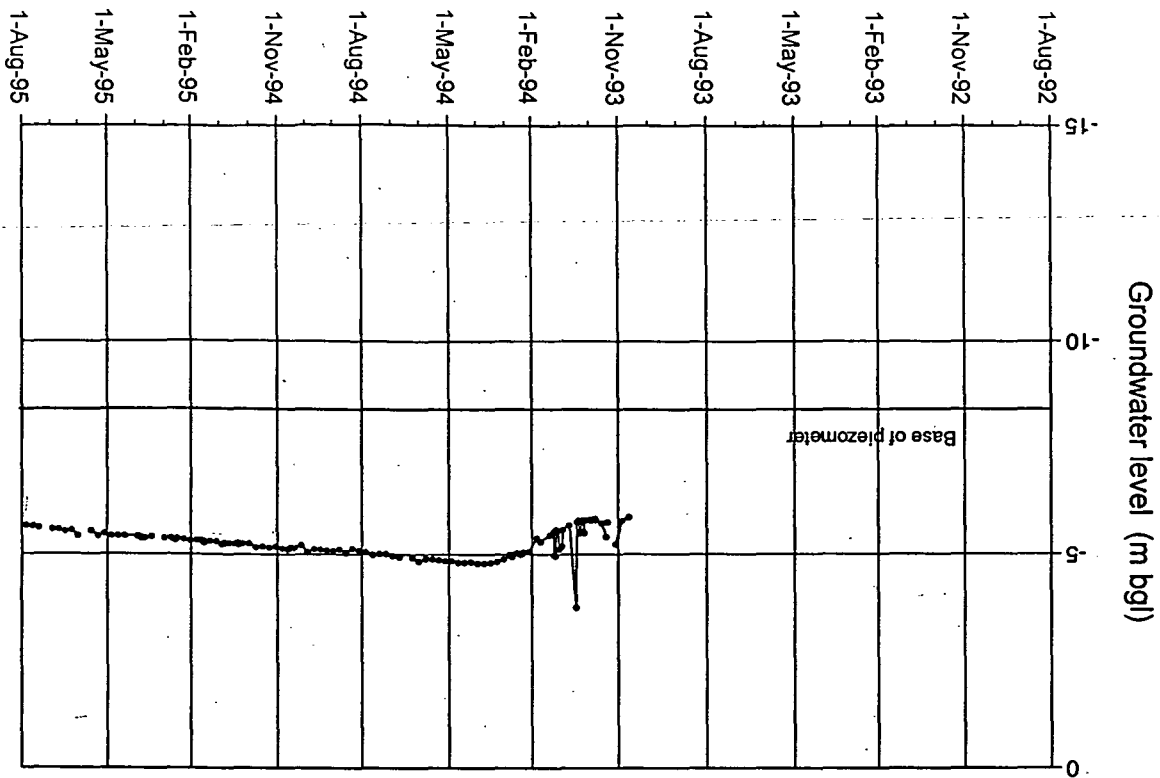
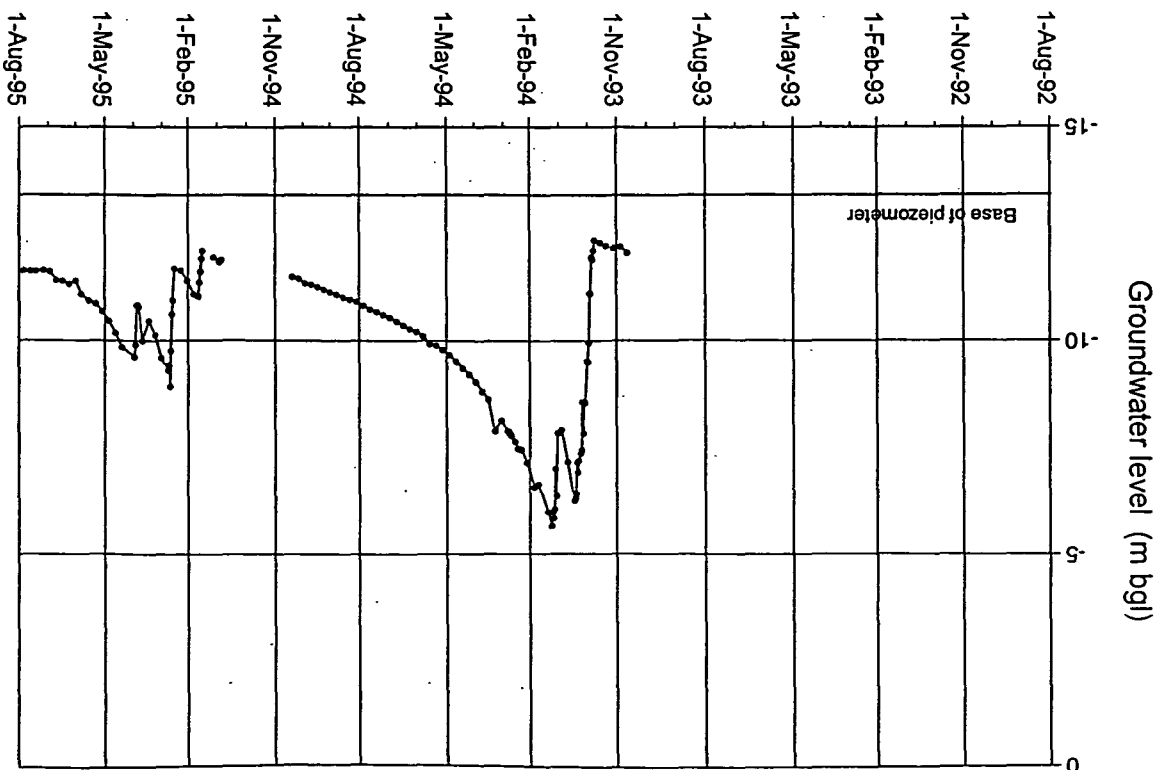


Figure 4.11a Depth to groundwater, start of monitoring to August 1995: Piezometer N5, Romwe Catchment



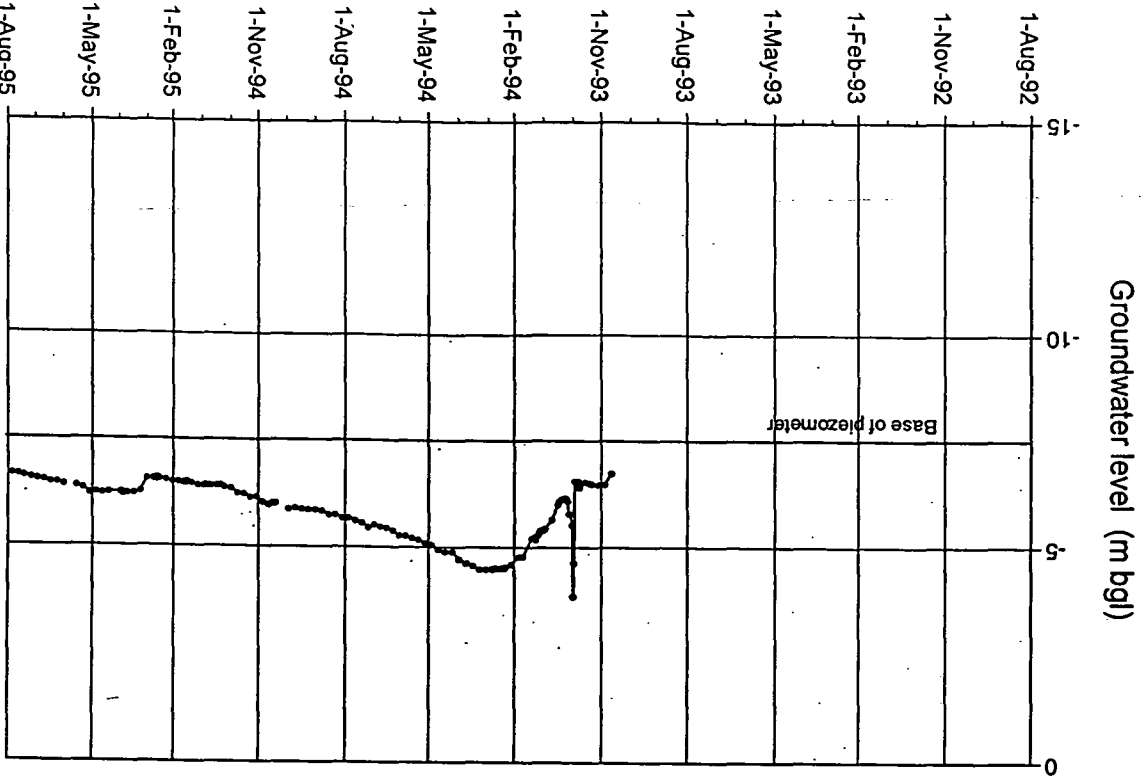


Figure 4.11c Depth to groundwater, start of monitoring to August 1995: Piezometer G, Romwe Catchment

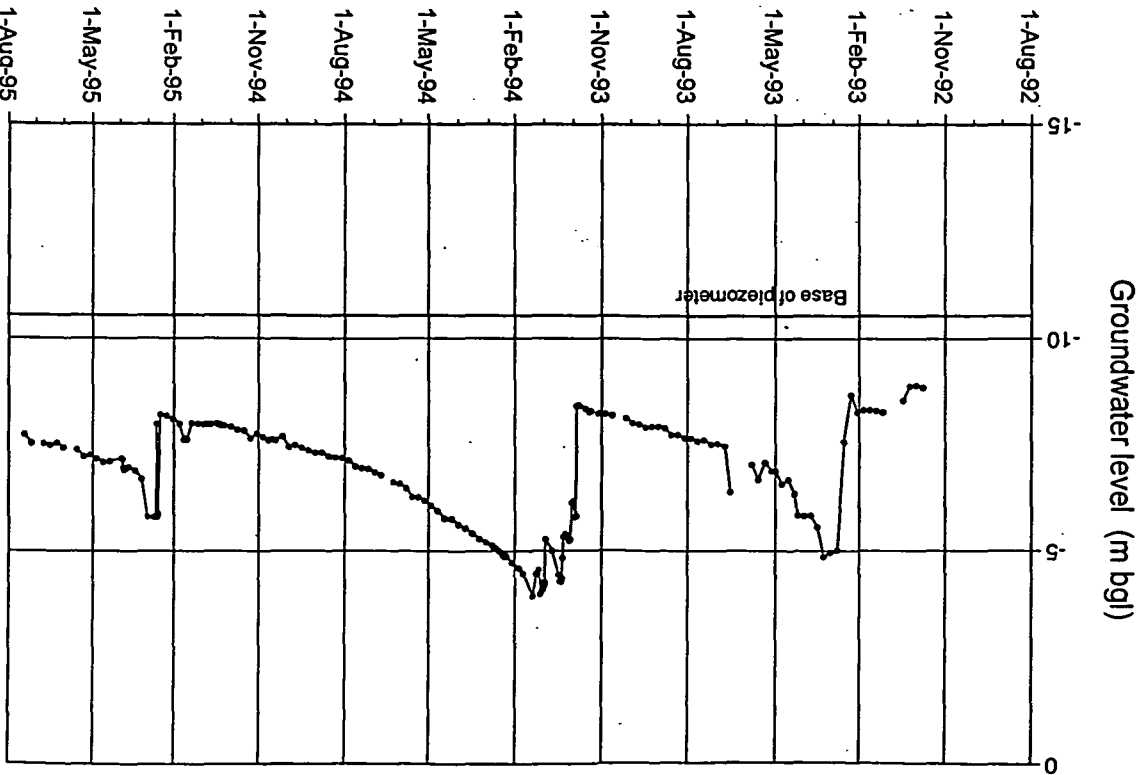


Figure 4.11d Depth to groundwater, start of monitoring to August 1995: Piezometer K2, Romwe Catchment

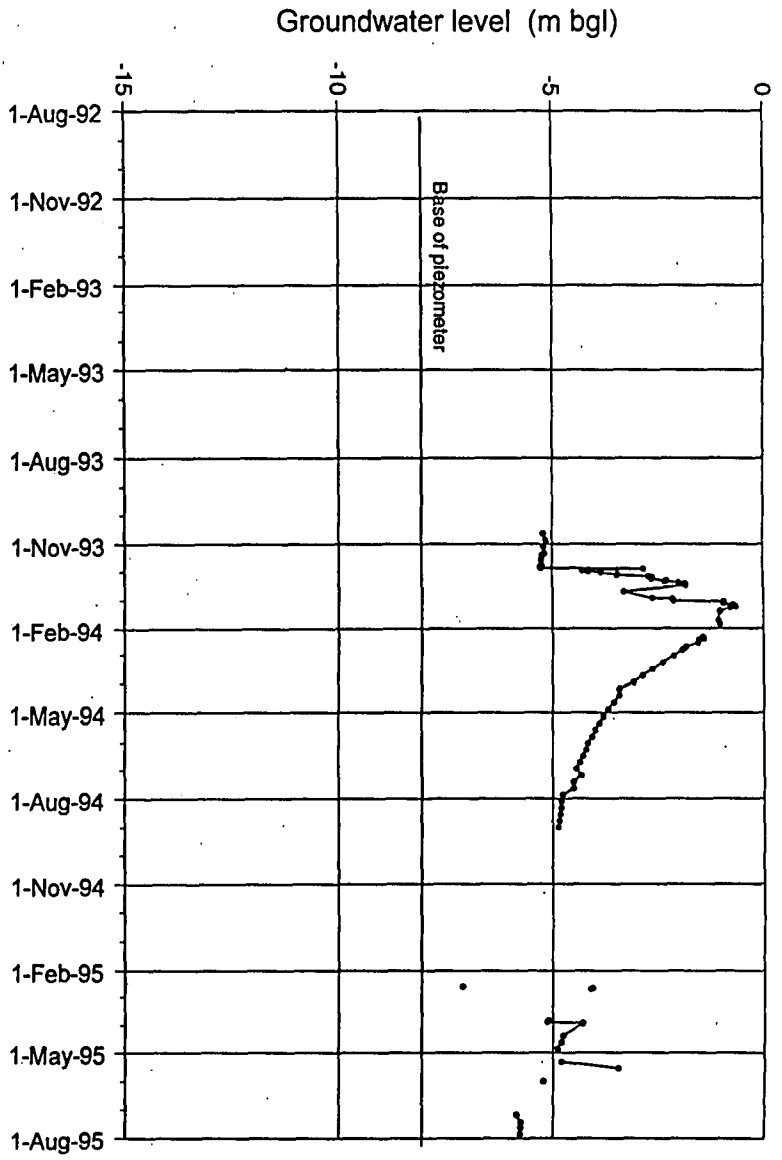


Figure 4.11e Depth to groundwater, start of monitoring to August 1995: Piezometer O, Romwe Catchment

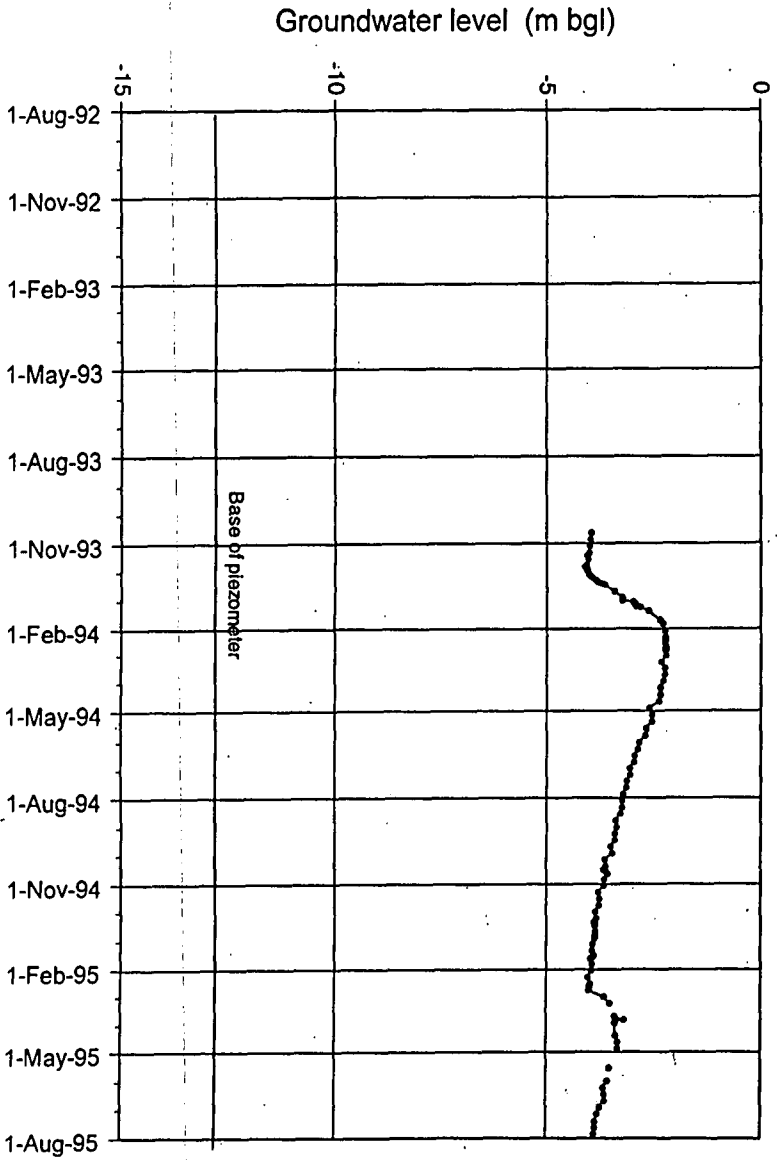


Figure 4.11f Depth to groundwater, start of monitoring to August 1995: Piezometer Q1, Romwe Catchment

from the streambed it is noticeable that on the northern side the depth to water-level is greater on average than on the southern side.

The spatial trend is also evident in the magnitude of the rise from the minimum to the maximum water-level in response to groundwater recharge. The largest rise, 6.86 m, occurred in N5 and the smallest, 0.8 m, in L2. In addition, a significant correlation exists between the groundwater rise and the depth to minimum water-level, with the larger rises occurring in the piezometers with the greater depths to minimum water-level.

#### *Rate of rise and fall of the water-level*

The faster groundwater rises were also the larger. Typically the peak was reached within 30 days of the minimum water-level, at a rate of 10-25 cm/day. The magnitude of the rise ranged between 3 m and 7 m. These responses occurred more often on the northern side of the catchment and were more extreme at the base of the steeper hills. Piezometer N5 (Figure 4.11a) was an example of such a response.

The slower rises are the smaller. Typically the peak was reached in over 100 days at a rate of 1 cm/day, and in the case of L7, 180 days (Figure 4.11b). The rise in L7 was less than 1 m. This type of response was found mostly on the southern side of the catchment.

#### *Transects to investigate localised recharge*

Three series of piezometers were sited to investigate localised recharge, the L-section, the U-section and the N-section (Figure 4.4). Piezometers L1 to L7 are located across a gully on the southern side of the catchment and piezometers U1 to U9 across the main stream that runs down the centre of the catchment. Water-levels in these piezometers did not suggest that these surface water bodies were major sources of groundwater recharge at these locations.

The piezometers N1 to N6 were located to monitor the localised recharge occurring due to the runoff from the inselberg and nearby hills in the north-west of the catchment. Unfortunately, not all the piezometers were deep enough to intercept the water-table; only piezometers N5 and N6 monitored water-levels for a significant period of the year. These piezometers showed relatively large and fast responses in water-level to rainfall events. This is likely to be due to a combination of the high transmissivity of the weathered zone in this region and the significant supply of potential recharge from the bare outcrops; two factors which may be linked.

Both of these localised recharge processes are being investigated in more detail in the work being carried out by IH in the catchment.

#### 4.3.3 *Chloride balance*

The chloride balance method for estimating regional values for groundwater recharge is discussed in Edmunds *et al.* (1988) and Edmunds and Gaye (1994). In summary, the method uses a balance of chloride in rainwater and in groundwater to allow a value of groundwater recharge to be calculated from the magnitude of effective rainfall. Chloride is a conservative ion; it is not removed from the soil layer by atmospheric evaporation or by transpiration from plants. If no other source of chloride exists other than the atmosphere, and soil erosion is not a major factor for removing chloride sources, then the flux of chloride through the soil surface will be the same as the flux into the saturated zone of the aquifer.

The concentration of chloride in groundwater was measured by sampling boreholes and wells. It is assumed that as it was averaged over a significant number of samples, a good approximation of the chloride in the groundwater was obtained. The chloride in the rainfall was only available for one year. This is unlikely to be equivalent to the long-term average input to the unsaturated zone but has been used to allow an estimate to be made. The weighted mean of the rainfall chloride was calculated using chloride concentrations from

samples collected for each rainfall event in 1993/94. Using this data the average recharge to the aquifer over the whole catchment obtained was 17 mm. This calculation assumes that all precipitation infiltrates the soil surface and that no interflow takes place. This is clearly not the case and, though these components are likely to be small, the recharge value is an overestimate. A better estimate will be possible when the surface water measurements from the instrumentation installed by IH are available.

The value of recharge obtained was calculated using a mean chloride concentration for groundwater in the catchment. However, Figure 4.12, which shows the groundwater chloride variation across the catchment, highlights a close correlation between chloride and the underlying geology. As mineralogical investigations proved there to be no source of chloride in the parent rock, it is assumed that the variation in chloride must be an indication of differing levels of groundwater recharge. Recharge was calculated using groundwater chloride concentrations averaged over the two dominant geologies of the low-lying areas. In the area underlain by pyroxene gneiss (with the higher mafic mineral content) on the northern side the value for recharge obtained was 24 mm. In the area underlain by leucocratic pyroxene gneiss, on the southern side the recharge was 8 mm. A comparison of these two values assumes that the runoff and interflow are similar on both sides. However, preliminary surface water measurements and hydrogeological investigations suggest that on average both runoff and interflow are greater on the southern side. Hence the ratio of recharge on the northern side to that on the southern side of the catchment is likely to be even greater than estimated above.

#### 4.3.4 *Penetration rates and falling-head tests*

It would appear that the nature of the weathered aquifer may have some control on the quantity of groundwater recharged. To investigate this hypothesis further, the drilling penetration rates and logs for the piezometers were analysed. This data was studied in combination with the results from falling-head tests that were carried out on a number of the piezometers.

The penetration logs give the time taken for a drilling rod of 0.75 m to penetrate the formation. Taking into account the type of drill bit (both drag bit and hammer bit were used), the penetration rate should give an idea of the form of the weathered layer.

Some spatial correlation is found in the penetration rate variation with depth. The drilling of piezometers K1, K2, the L-section, S and U7-U9, which are in the leucocratic pyroxene gneiss unit on the southern side of the catchment, identified a layer of clayey material 3 to 5.5 m thick at a depth of 0.5 to 1.5 m below the soil surface. The average penetration rate through this horizon using a drag bit was 12 min/metre. This compares with an average penetration rate in the weathered material below the horizon of 4 min/metre. In piezometers H, K4, N4-N7 and T, in the pyroxene gneiss unit on the northern side, the penetration rates through the weathered zone using the drag bit are faster, on average 1 min/metre. The penetration rates do not vary greatly from this average value. The average depth to bedrock in the two units are also noticeably different, approximately 7 m in the leucocratic pyroxene gneisses and 10.3 m in the pyroxene gneisses.

Additional data on the aquifer formation was obtained from a number of falling-head test carried out on piezometers. The tests were not fully analysed but the relative decline in water-levels during the tests were compared across the catchment. Though some anomalies were evident, the test results also showed a correlation with geology; a faster recovery in water-levels during the tests occurred in the piezometers located in the weathered zone of the pyroxene gneiss.

#### 4.3.5 *Discussion of recharge investigations*

The previous sections have presented the results of a number of techniques employed to investigate groundwater recharge in the Romwe catchment. These different approaches show a significant spatial correlation in groundwater recharge. In general, the greater levels of recharge occur on the northern side of

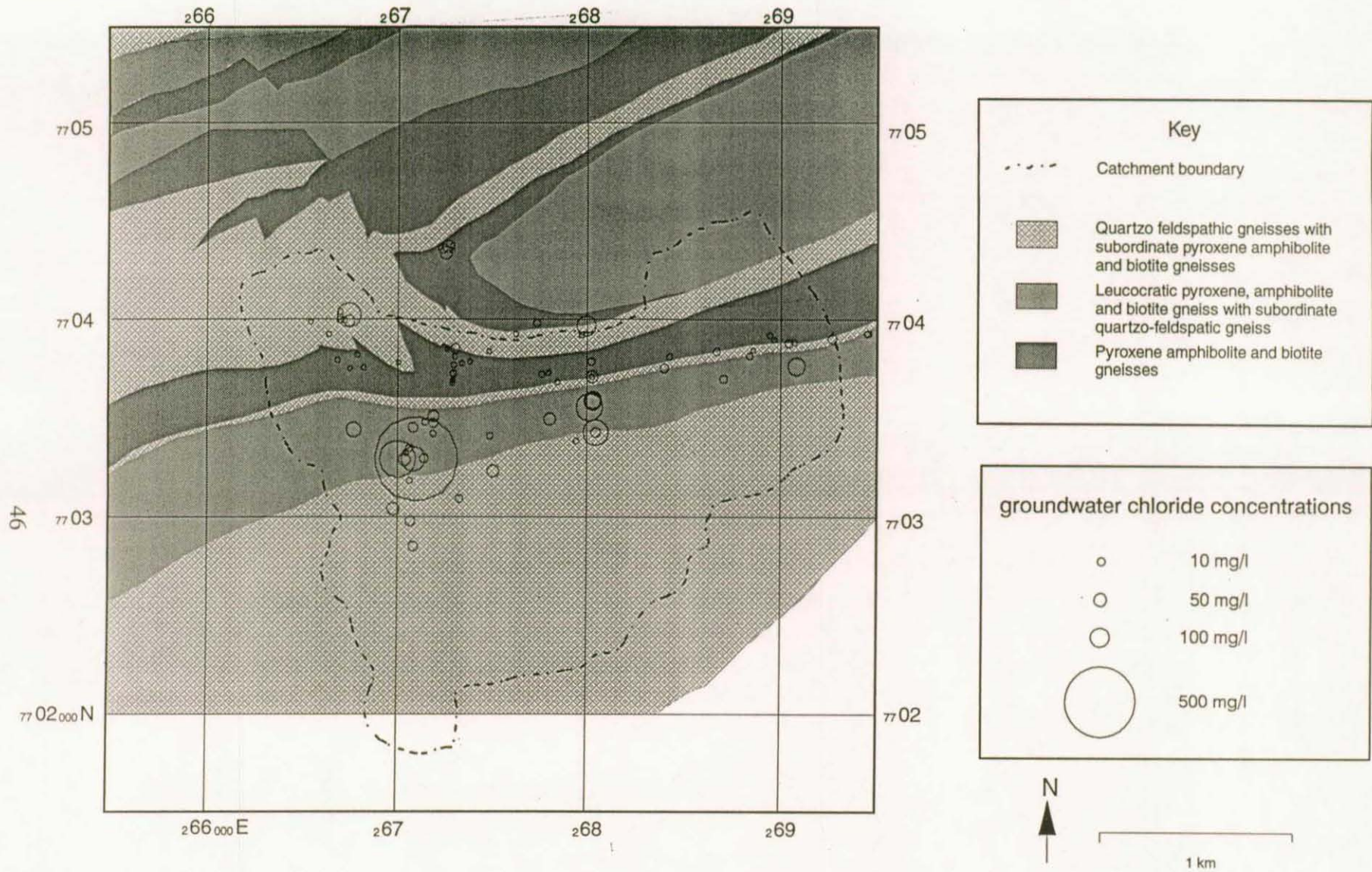


Figure 4.12 Groundwater chloride concentrations measured in wells and piezometers, March 1994, Romwe Catchment

the catchment where the mineral content of the parent rock is higher in mafic minerals (pyroxene gneiss). Here the groundwater level rise is greater and occurs at a faster rate and the depth to the water-table is greater at the end of the dry season. Although water-level data alone cannot be conclusive, as a large rise may be due to a lower storage coefficient, the results of the chloride balance also show recharge to the weathered zone here to be greater. The evidence obtained on the form of the weathered layer in the leucocratic pyroxene gneiss suggests a layer of low permeable clay (upper saprolite) exists across most of the southern side of the catchment. This appears to reduce the effective recharge to the underlying aquifer and cause a significant proportion of water infiltrating the soil layer to become interflow. The greater occurrence of water-logging of soils on this side of the catchment is evidence of the existence of the resulting perched water. It is also likely that the clay layer causes confined or semi-confined conditions to occur in the weathered aquifer on the southern side.

Piezometers in the north-west corner of the catchment show a particularly large and fast rise in water-levels in response to rainfall. A combination of factors contribute to this: the bare outcrops to the north provide a good catchment for potential groundwater recharge; significant groundwater throughflow (aided by the series of fractures running perpendicular to the valley) has promoted advanced weathering of the bedrock; and the mineralogy of the parent rock has allowed a relatively permeable weathered zone to develop.

Results from the IH component of the study show that the soil may also have a strong control on recharge across the catchment. The grey soils on the southern side of the catchment are less coherent and more prone to crusting with the result that runoff is more likely to occur. On the northern side of the catchment the red soils are more coherent. This increases the roughness of the soils, reducing runoff and enhancing infiltration.

It therefore appears that both the nature of the weathered profile, and the soil layer, allow greater volumes of water to be recharged to the aquifer underlying the northern side of the catchment.

In addition to the soil and geology, groundwater level monitoring also shows that recharge will only occur in response to large rainfall events. Smaller, widely spaced events are often not able to overcome the soil moisture deficit and evapotranspiration. Initial results from 1994/95 season confirm what was seen in 1993/94. In the early part of the wet season in 1994/95, though there was a reasonable quantity of rainfall, the temporal distribution meant that there was no noticeable recharge. But for one major rainfall event of 141 mm in the late wet season, recharge would have been negligible.

#### **4.4 Conclusions from the Romwe case study**

Pumping-test results show that in general the weathered layer in the pyroxene gneiss unit on the northern side of the Romwe catchment has a higher transmissivity than in the leucocratic pyroxene gneiss on the southern side. Water-level and abstraction monitoring confirm that the productivity of wells on the northern side of the catchment, and especially in the north-west, is greater. Piezometers in the vicinity of wells on the southern side show that steep cones of depression develop during the dry season, that in many cases cause the wells to effectively dry-up. This is due to the lower permeability of the weathered layer as a whole, caused by the existence of a significant thickness of clay (upper saprolite) at shallow depths. It is suggested that the fast recovery of these wells, in response to large rainfall events, may be due to the interception of interflow by the wells. The steep cone of depression means that the volume of aquifer dewatered around the well is quite small and therefore can be replenished quickly.

The catchment therefore presents two differing stories of sustainability. On the southern side many wells cannot be considered sustainable over the period of a dry season. This is due to the low permeability of the aquifer and the reduced recharge caused by the thick upper saprolite and the soil type. In addition, the recharge will be proportionally less on this side of the catchment during low rainfall years.



In a normal rainfall period the wells on the northern side are sustainable over a dry season, but their sustainability is questionable during extended periods of low recharge. Recharge will be reduced when yearly rainfall totals are low but also when rainfall occurs as smaller well distributed events. Without recharge the natural groundwater gradients that exist within the weathered aquifer will cause water-levels to fall, especially where the aquifer is more permeable. If a drought occurs during a long period of below average rainfall, as happened in 1991/92, the added stress on the aquifer system with its relatively small storage is likely to cause severe water supply problems. Monitoring of water-levels in the wells on the northern side showed a gradual recovery over the two years following the 1991/92 drought though they were again recessing due to the rainfall pattern in 1994/95.

The control that the parent rock mineralogy and texture has on the properties of the weathered aquifer and on groundwater recharge has important implications for well and borehole sustainability. It has relevance for the siting of groundwater sources in regions where small-scale variations in the mineralogy occur over hundreds of metres. The implications of the results of this case study will be taken further in the overall discussion of the report in Chapter 6.

One option for groundwater development has, however, been tested within the Romwe catchment, the collector well constructed in 1991 prior to the drought of 1992. The greater depth and storage and the increased effective radius and reduced drawdown in the well as a result of the laterals, meant the well could provide water throughout the period of the drought. A comparison of the sustainable yield of a number of well and borehole designs is made in the following chapter.

## 5. A COMPARISON OF THE PERFORMANCE OF WELL TYPES

In addition to both spatial and temporal variations in recharge, the Romwe case study has highlighted low permeability of basement aquifers as a major control on the sustainability of yield from wells and boreholes. Low permeability can often restrict the volumes of water that can be abstracted due to the steep cones of depression that develop around wells. Though a long-term reduction in recharge may cause the overall groundwater resource to decline, local dewatering of the aquifer can have an equal if not greater detrimental effect on the sustainability of the source. Those developing the groundwater resource have some control of this aspect of sustainability through the design of the abstraction point.

In Chapter 3 the objectives of the pilot project "Small-scale irrigation using collector wells" were discussed. These included a comparison of the sustainability of yield of various well designs via a series of pumping-tests carried out on wells and boreholes at nine collector well sites. The analysis of the pumping test data obtained were undertaken in collaboration with the "sustainable yield" project. The methodology and results are presented in this chapter (they were also presented in Lovell *et al*, 1995).

### 5.1 Well designs

#### *Traditional dug well*

In Africa, the traditional source of groundwater is the dug well. Generally, these are dug by hand using chisels and picks and a bucket and windlass to remove the spoil, but without the aid of a dewatering pump. They are usually 1-1.2 metres in diameter. The level of abstraction sustained is generally low but can be sufficient to supply a family with water for domestic use and for irrigating a small garden. The depth of the well is controlled by the water-table and primarily by the degree of weathering in the upper layers of rock. The well cannot be dug much below the water-table without the aid of a dewatering pump. Deepening of the well is achieved progressively during periods when the well is dry. Government organisations and NGOs have sponsored the deepening of traditional wells (often using explosives) as one option for dealing with groundwater drought. In Zimbabwe, a programme of well deepening is presently being undertaken in response to the recent sustained period of below average rainfall and the general increase in demand for water due to the rise in population.

#### *Large-diameter well*

Large-diameter wells (2-3 m) like traditional dug wells are constructed within the weathered zone. They are dug by hand but with the use of handtools that may include a pneumatic jackhammer and de-watering pump to allow construction below the watertable. The depth of the well is controlled by weathering and the required volume of water, digging usually stopping when fresh rock is encountered (at depths typically of 10-15 metres in the "small-scale irrigation" project). On average, the depth of a large diameter well would be greater than the traditional dug well, increasing the chances of intercepting the relatively more productive zone which is often found at the base of the regolith. Abstraction sustained by such a large diameter well will also be higher than a traditional dug well due to the greater wetted surface area allowing increased inflow and the greater volume of storage. These types of wells are rarely constructed in Zimbabwe but are common elsewhere eg India.

#### *Collector well*

As already mentioned the overall transmissivity of the weathered basement aquifer is low. This lower transmissivity can cause cones of depression to develop in the water-table around wells. As illustrated in Chapter 4, water may be available beyond the cone of depression but the hydraulics of the system do not allow the well to tap it. The collector well was designed to overcome this problem of localised drawdown in the water-table. It is a large-diameter well constructed as described above but with boreholes (laterals) mechanically drilled sideways from its base. As many as six laterals may be drilled to distances of 30 metres

using a specialised drilling rig. They increase the effective radius of the well and reduce the drawdown in the surrounding aquifer. Another advantage in the highly variable conditions encountered in weathered basement aquifers is that the laterals may pass beyond localised discontinuities and tap zones of higher productivity.

### ***Boreholes***

Narrow boreholes (or tubewells), 15-20 cm diameter, are the most widely constructed type of abstraction point in groundwater development programmes. Being mechanically drilled they are easier to construct and can be completed in a relatively short time. The aquifer tapped by boreholes depends on the depth of the weathered zone. In south-east Zimbabwe, the relatively thin overburden (combined with a lack of understanding of the potential of the weathered zone) has meant that the vast majority of boreholes penetrate the fractured bedrock in search of fractures which may yield significant volumes of water. Depths of 50-70 m are typical. Where interconnected fractures occur in the unweathered basement they can allow deep boreholes to draw on the higher storage of the regolith. If major water bearing fissures are intercepted which produce locally high transmissivity, high yields can be achieved. However, the pattern of fracturing in crystalline bedrock is highly variable and not easy to predict. Many boreholes do not intercept fracture systems that are sufficient to satisfy either volume of water or the longevity of supply required; poor drilling success rates reflect this difficulty. Generally, the weathered zone of boreholes is cased rather than screened. This reduces costs but denies direct access to water from the upper aquifer. Though boreholes are mostly unlined in the bedrock, where they are lined, yield can in time be reduced by a build-up of material on the screen, requiring maintenance.

## **5.2 Factors influencing the choice of well type**

A number of factors influence choice of well type and should be considered during a water development programme in crystalline basement rock.

### ***Weathered zone***

The principal physical factors influencing the choice of well type are the nature and thickness of the weathered zone, and the position of the water-table (which relates primarily to the climate). These factors determine the permeability and saturated thickness of the shallow weathered aquifer. Where the regolith is very thin or absent dug well construction may be virtually impossible and boreholes may be the only option. If the regolith is thick and water table shallow, dug wells are more likely to be viable.

The advantage of dug wells, particularly in low permeable aquifers, is that the large storage of the well can be tapped during the day, allowing the well to recover overnight. The storage of a borehole is relatively small and therefore in low permeable aquifers pumping may result in significant levels of drawdown that cause reduced abstraction rates.

Natural groundwater quality is also an issue in the choice of well type, for example where saline water is found at depth the usefulness of boreholes will be limited.

### ***Community preference and sense of ownership***

Ensuring local involvement in designing, implementing and managing water projects brings the greatest chance of success. Sense of ownership and responsibility for upkeep of a water point is more likely if the well is dug by the community rather than drilled by an external agency.

### ***Pump capacity and ease of repair***

Rural farmers owning traditional wells generally use a bucket and windlass to abstract water. Communal wells, however, are often fitted with a pump. The nature of the rural environment prohibits use of high technology pumps. A source of power is rarely available or within peoples means and the necessary tools

or skills may not exist to repair such equipment. Simple hand-powered single action reciprocating pumps (eg Zimbabwean Bushpump) are thus most often used. These pumps are typically able to supply 5-10 m<sup>3</sup>/day. A borehole will only allow one such pump to be fitted: the borehole may thus be under-utilised if the potential yield is greater than the pump capacity. A large-diameter well in contrast will allow several pumps to be fitted. This has the advantage that there should be less wear and tear per unit and further, that when one pump breaks water may still be abstracted from the other(s). In addition, the smaller storage of a borehole may result in a greater water-level drawdown within and hence a greater height over which to lift the water. This will cause more strain on the pump bearings. This strain will also be increased by the weight of pump rods and rising main that are greater in deep boreholes.

In development programmes community-maintenance of both well and pumps is the ultimate goal. Irrespective of well design, this requires training of local people and provision of tools, but is made easier on a dug well than on a borehole due to the shallower depth and corresponding lighter pumping unit that has to be extracted.

### *Cost-effectiveness*

Development organisations will wish to choose the well type that results in the most effective use of the money available. Some factors within the provision of wells can easily be given an economic cost. These include drilling or digging, staffing and construction materials. It may be more economic to drill two boreholes than dig one large-diameter well or dig two large-diameter wells than one collector well. For other factors, however, it may be difficult to give an economic value such as the sustainable yield from the well. It was with the aim of improving the understanding of this component of well choice that this case study was undertaken.

## **5.3 Methodology**

As discussed in Section 3.2, a technical cooperation project was undertaken in south-eastern Zimbabwe during which a procedure for setting-up communal plots for the growing of garden vegetables using groundwater for irrigation was developed. Eight sites were established, six funded jointly by the Southern Africa Development Division of ODA and the Government of Zimbabwe (GoZ), and two by the NGO, Plan International. The location of these sites can be seen in Figure 3.3. At each of the sites large-diameter wells of approximately 2.1 m diameter was dug to approximately 15 m and in seven of the eight these large-diameter wells were converted into collector wells by drilling 4-6 boreholes laterally out from the base to a maximum of 30 m. The six ODA/GoZ sites (sites 1-6) were constructed in crystalline basement rock; the two Plan International sites (sites 7 and 8) were constructed in Karoo basalts (7 was not converted to a collector well as it was thought to be productive enough as a large-diameter well). The two Plan International sites will be discussed separately in Section 5.5 but their details will be included in the tables that follow. At all the sites the wells were sited by exploratory drilling which was used to identify significant thicknesses of saturated weathered overburden.

### *5.3.1 Pumping-test procedure*

The technical cooperation project provided the opportunity to compare well types at six sites in crystalline basement. The procedure for comparing the well types was as follows:

- Step 1 Pumping-tests carried out on the available wells at each site.
- Step 2 Pumping-tests analysed to obtain values for aquifer parameters for the shallow weathered aquifer and the deeper fractured bedrock aquifer at each site.

Step 3 Aquifer parameters for the shallow layer used to analyse pumping-tests on the collector wells by allowing the effective radius of the well to vary.

Step 4 Computer simulation of abstraction from wells and boreholes to obtain the maximum sustainable yield for the period of one dry season.

Tests were carried out at all sites on the large-diameter well and the collector well. Where possible additional tests were carried out on: one of the shallow exploratory boreholes drilled during well siting; the shallow exploratory borehole deepened to 40 m; a communal borehole and in a few cases a traditional small diameter well. The design of the communal borehole was not always known but the government organisation which construct these boreholes generally case off the weathered zone. The tests that were carried out at each site are shown in Table 5.1 along with the geology of the area and the approximate mean annual rainfall.

**Table 5.1 Details of geology, rainfall and well depth at the eight collector well garden sites. The length of laterals drilled for each collector well are also included**

Site	1	2	3	4	5	6	7	8
Geology	gneiss	gneiss	gneiss	granite	gneiss	gneiss	basalt	basalt
Annual rainfall (mm)	780	790	780	?	820	785	580	580
LDW	15.8	15	15	15	13	9.5	8.76	18
CW laterals (no.+length)	5 15,4x30	4 4x30	5 8,9,25, 27,28	4 18,3x30	4 14,16.5, 28.5,30	5 1.5,4,8, 23,30	none	4 9,19,27,2 7
TW	-	-	-	12.75	-	-	-	-
SEB	15	15	-	15	15	15	18	-
DEB	40	30	-	-	33	-	-	30
DCB	48	-	43	-	39	-	-	-

LDW large-diameter well  
 CW collector well  
 TW traditional well  
 SEB shallow exploratory borehole  
 DEB deep exploratory borehole  
 DCB deep communal borehole

The pumping-test programme developed as the collector well garden project progressed. Due to a restriction on time the initial plan to carry out both a high discharge and low discharge test on the large-diameter well and the collector well had to be cut-back to a single medium discharge test. The average pumping rate and pumping time for each test is summarised in Table 5.2. The tests on the communal deep borehole were carried out with the help of local people using the handpumps.

### 5.3.2 Pumping-test analysis

#### *Complexities of the basement aquifer*

A pumping-test can be used to estimate the properties of the aquifer within which a well is situated. Drawdown due to pumping and the subsequent recovery of the water-level with time are monitored. By

fitting the water-level response to a mathematical model the aquifer properties can be estimated. The mathematical model is a simplification of the aquifer system.

**Table 5.2 Details of pumping-tests at the eight collector well garden sites**

Well type	Pumping rate (litres/sec)	Pumping time (mins)	Site
LDW + CW low discharge	0.65	120	1,2
LDW + CW high discharge	4.5	120	1,2
	2.65	240	3,4
LDW + CW medium discharge	1	300	5,6,8
SEB	0.4	60	1,2,4,5,6,7
DEB	0.6	240	1,2,5,8
DCB	0.6	60	1,3,5

LDW large-diameter well  
 CW collector well  
 TW traditional well  
 SEB shallow exploratory borehole  
 DEB deep exploratory borehole  
 DCB deep communal borehole

Crystalline basement rock forms complex aquifers. The weathered shallow aquifer and the deeper bedrock aquifer are quite different in form. The weathered aquifer can vary greatly in thickness over short distances and in composition both vertically and laterally. Its permeability will tend to increase with depth as the proportion of secondary clay minerals reduces (Chilton and Foster, 1995). The saprock has a high fracture permeability. The bedrock permeability depends on the density and connectivity of the fractures. The boundaries between the saprolite and the saprock and the saprock and the fresh bedrock are not usually sharp. The form of the aquifers will change from site to site as they are dependent on the lithology of the parent rock and the tectonic, climatic and geomorphological history. Even at one location the lateral variation may have hydraulic significance, for example where hard bands in the rock form flow barriers.

This complex nature means that it is difficult to describe crystalline aquifers with a mathematical model. There may not be a single set of parameters that define the hydraulic system. One method of incorporating the complexities of the system is to set-up a detailed numerical model. This type of model is very time-consuming to develop, requires detailed input data and can be site specific. It was decided that the only practical approach was to use a model that simplified the system. The limitations of this approach are considered when discussing the results.

***Pumping-test analysis program BGSPT***

The program used for the pumping-test analysis in this study is an in-house BGS computer model, BGSPT (Barker, 1989). The package consists of two programs: PTFIT, which analyses pumping-test data; and PTSIM which simulates well drawdown using a specified set of well and aquifer parameters. PTSIM is used to estimate the sustainable yield of the wells. PTFIT accepts ranges of aquifer parameters as input. It then

optimises the fit of the pumping-test data to the built-in conceptual model by varying the parameters within these ranges. The conceptual model is that of a fully penetrating well in a semi-confined homogeneous aquifer of infinite extent. The semi-confining aquitard can be confined or unconfined. Flow within the aquifer is assumed to be horizontal and within the aquitard, vertical. The water-table in the aquitard is assumed to be horizontal. The model does not apply where the drawdown in the well is great.

The well geometry is defined by the radius of the casing,  $R_c$ , and the screened section of the well,  $R_w$ . Within this project the program has been developed to allow the radii to be varied along with the other parameters. This development has allowed the increase in the effective radius of the large-diameter well due the laterals to be estimated. The variation of the radii also account (in an approximate manner) for the effects of partial penetration of the aquifer and the possible existence of a seepage face. The model has the advantage over many other computer models that it can deal with large-diameter wells. Though the model allows for a semi-confining layer the information required as input to the model for the layer was not available. The aquifer in all cases was therefore assumed to be confined. The assumption of confined conditions means the model reverts to that proposed by Papadopolous and Cooper (1967). However, there is some justification in this assumption as at most sites the depth of the first-strike of water during the drilling of the exploratory boreholes was well below that at which the static water-level was eventually measured. It is unlikely, however, that the weathered aquifer remained confined throughout the period of the pumping-test.

Other assumptions made by the model of the aquifer system are also not valid for the sites and tests in this study. The aquifer does not extend infinitely and drawdown in the wells is not small compared to the saturated thickness of the aquifer. However, the assumption that the wells are fully penetrating is reasonable as the wells were completed at the base of the weathered zone.

## **5.4 Results of the pumping-test programme**

### **5.4.1 Difficulties experienced in pumping-test analysis**

As expected a number of difficulties were experienced in the analysis of the data obtained from the pumping tests. In some cases data could not be fitted to the model without allowing the input parameter ranges to be set at unrealistic values. In particular the fitting of storativity was problematic. Values were obtained that were higher than would be expected, even for unconfined aquifers. In addition, inconsistent parameters resulted from tests at the same site in the same aquifer. As well as the invalidation of some of the assumptions of the conceptual model a number of causes have been suggested for the problems experienced.

Rarely were rest water-level conditions obtained prior to the start of a test. Both the large-diameter and collector wells were dewatered to allow the digging and drilling to be carried out. The time required for the full recovery of these wells and the subsequent pumping-tests would have affected the progress of the "small scale irrigation" project and withheld a vital source of water from local people. The result of a test being started from a non rest water-level is that the recovery from the test is combined with the recovery from the pumping prior to the test. This has particular relevance to tests where the pumping drawdown is relatively small; where this occurred, compensation was made in the analysis.

At some sites, fractures in the vicinity of the well may have increased its effective storage causing a lower water-level decline than expected. At other sites, if a seepage face developed in the well in response to pumping, the drawdown may have been greater than expected.

In light of these problems and the simplifications made in the model, results presented below should be considered indicative rather than absolute. However, the modeller was able to indicate a level of confidence that could be placed in the results obtained for each site on the basis of: the sum of the errors of the modelled

fit; consistency of results at each site; and the comparison of predicted drawdown, using the modelled parameters, and performance of individual wells. The confidence level ranges from 1 (low) to 5 (high). Results obtained for the first collector well completed in Romwe catchment in Chivi District in 1991 are also included.

#### 5.4.2 *Aquifer properties*

Table 5.3 shows aquifer properties determined at each site using pumping-test results for the various wells. Transmissivities in the deeper aquifers are generally greater than in the shallow aquifers and storativity smaller. However, there are exceptions and some important implications for the performance of different well types in these aquifers:

**Site 1:** there is a noticeable difference between the values obtained for the transmissivity and storativity of the deeper aquifer from the communal and exploratory borehole tests. As the confidence in these results are reasonably high this may suggest heterogeneity in the aquifer.

**Site 2:** the parameters obtained for the deep aquifer are not significantly greater than for the shallow aquifer. This suggests the deep exploratory borehole has not managed to intercept a productive network of fractures.

**Site 3:** the communal borehole is extremely productive due to a very high value of transmissivity for the deeper aquifer.

**Site 4:** the communal borehole test gave a value of transmissivity that is smaller than that for the shallow aquifer. Though confidence in this result is not high it is likely that this communal borehole has not intercepted a productive network of fractures.

**Site 5:** both the communal borehole and the deep exploratory borehole tests suggest low values of transmissivity for the deeper aquifer. The shallow aquifer here has the highest value of transmissivity of all the crystalline basement sites.

**Site 6:** no deep borehole was available to test. The shallow aquifer gave a high value of storativity suggesting that the assumption that the aquifer is confined here is not valid.

#### 5.4.3 *Effective radius of collector wells*

The parameters obtained from the shallow aquifer tests on the large-diameter well and/or the shallow exploratory borehole were applied to the collector well pumping-test and the data fitted to the model by allowing the effective radius to vary. Predictions based on modelling were verified using measured well performance; abstraction and resultant well drawdown have been monitored at the collector well sites since their completion. The values of the effective radius determined, along with confidence levels, are given in Table 5.4. The radius of the large-diameter well in each case is 1.05 m.



**Table 5.3 Pumping-test results for the shallow and deep aquifers at the eight collector well garden sites and the Romwe catchment**

Site	SHALLOW AQUIFER					DEEP AQUIFER				
	Depth of well (m)	T (m <sup>2</sup> /d)	S	Conf	Source of test data	Depth of borehole (m)	T (m <sup>2</sup> /d)	S	Conf	Source of test data
1	15	0.8	0.005	4	LDW	48	32.0	2e-6	4	DCB
						40	4.48	0.0050	4	DEB
2	15	1.4	0.008	4	LDW	30	2.4	0.0080	4	DEB
3	15	2.9	0.007	1	LDW	43	118.0	0.0070	4	DCB
4	15	2.9	0.010	3	SEB	25	0.9	0.0100	2	DCB
5	14	3.1	0.007	3	LDW	33	5.6	0.0009	3	DEB
						33	0.8	0.0070	2	DCB
6	10	2.5	0.077	4	LDW	-	-	-	-	-
Romwe	12	1.1	0.520	2	LDW	-	-	-	-	-
7	9	30.2	0.565	3	LDW	18	206	0.0020	3	DEB
8	18	9.8	0.004	3	LDW	30	9.8	1e-6	2	DEB

LDW large-diameter well  
 SEB shallow exploratory borehole  
 DEB deep exploratory borehole  
 DCB deep communal borehole

**Table 5.4 Effective radii of the eight collector wells and the Romwe collector well**

Site	Effective radius (m)	Confidence level
1	9.2	4
2	1.33	4
3	19.0	3
4	10.3	2
5	8.9	2
6	4.7	4
Romwe	1.35	2
7	-	-
8	1.85	4

## 5.5 Predicted levels of sustainable abstraction

### 5.5.1 Modelling methodology

To compare performance of the alternative well types at each site, measured aquifer properties and well dimensions were input to the PTSIM program within the BGSPT package. The model was modified to simulate a repeated cycle of daily abstraction pumping at 1.5 m<sup>3</sup>/hour for five hours in the morning (06:00 to 11:00) and five hours in the afternoon (13:00 to 18:00). This was repeated for 240 days, the average length of a dry season. The drawdown at the end of this period due to an abstraction rate of 15 m<sup>3</sup>/day was then scaled up or down to equal the maximum available drawdown, thereby giving the maximum possible abstraction rate. Available drawdown was taken to be the inlet depth of the pump for the shallow wells and two-thirds the depth of the borehole (the level of drawdown considered to give optimum abstraction for a borehole). An estimate of the regional recession in the water-table due to the natural groundwater gradient was also included in the drawdown in the well at each site.

The abstraction rate obtained from the modelling is an estimate of the maximum sustainable yield from each type of well over the period of one dry season. The results are shown in Table 5.5.

### 5.5.2 Discussion of results

Monitoring of water use from existing collector wells suggests an average abstraction rate of 15 m<sup>3</sup>/day is required. This provides enough water to irrigate a 0.5 ha garden and supply 50-100 families with most of their domestic water. Table 5.5 shows that at no site did a traditional dug well satisfy the requirement of 15 m<sup>3</sup>/day. This is due in part to the smaller diameter and depth typical of this type of well. It is also due in part to the method of well siting. A communal farmer is generally restricted to siting his well on his own land, ideally in a position where it is convenient to his house or garden. He may employ the skills of a water diviner but they would still operate under the above restrictions. In contrast, these large-diameter wells and collector wells were sited to serve the community, with little restriction on location and with the benefit of exploratory drilling to locate the preferred aquifer properties prior to digging the well. It is likely that a well of traditional diameter also sited in this way would have a higher yield.

Table 5.5 Simulated maximum sustainable yield for a period of 240 days at the eight collector well garden sites and the Romwe catchment

Site	LDW		CW		%imp	TW		DCB cased in WZ <sup>1</sup>		DEB screened in WZ		DEB cased in WZ	
	Qmax	Conf	Qmax	Conf		Qmax	Conf	Qmax	Conf	Qmax	Conf	Qmax	Conf
1	11.5	4	18.0	4	56	-	-	200	2	43	2	35	2
2	16.7	4	17.1	4	2	-	-	na		26	2	8	2
3	26.1	3	34.1	3	31	-	-	769	2	-	-	-	-
4	24.1	3	40.2	3	67	2.1	3	2	2	-	-	-	-
5	22.3	3	34.7	2	56	2.9	2	1.4	2	37	3	25	3
6	12.4	4	18.3	4	48	-	-	-	-	-	-	-	-
Romwe	10.2	3	10.8	3	6	1.6	2	-	-	-	-	-	-
7	47.0	3	na	na	na	-	-	-	-	-	2	347	2
8	55.3	4	62.5	4	13	-	-	-	-	-	2	<2	2

**WZ** weathered zone  
**LDW** large-diameter well  
**CW** collector well  
**TW** traditional well  
**DEB** deep exploratory borehole  
**DCB** deep communal borehole

At 4 of the 7 sites in crystalline basement, the large-diameter well is shown to supply the required volume of water. This improves to 6 of the 7 sites with lateral drilling. As might be expected, heterogeneity found in basement aquifers means that lateral drilling success varied from site to site. At site 2 and at Romwe the improvement was minimal. Overall, however, at the sites on the basement complex the average improvement was 38%. This improvement can be viewed in two ways. Radials can increase the maximum sustainable yield for the period of a dry season. Alternatively, radials increase the period for which a particular abstraction rate can be sustained. At site 1, for example, the large-diameter well could sustain pumping at 11.5 m<sup>3</sup>/day for 240 days before drying. The collector well would last for 300 days pumping at this rate. Clearly, this has important implications for villagers who need to continue watering their vegetables through a period of low recharge or an extended dry season, and therefore care must be taken when placing a value on this additional water. Any increase in yield made possible by lateral drilling cannot simply be divided by the additional cost of this operation.

Sites 7 and 8 characterise the role that geology can play in final choice of well type. Unlike weathered basement at the other sites, the shallow weathered zone of basalt at 7 and 8 is not pronounced. Instead, the groundwater flow is concentrated in zones of horizontal sheet jointing, and these zones both shallow and deep are highly transmissive (Table 5.3). Consequently, both large diameter wells and exploratory boreholes gave significant amounts of water. However, as digging was particularly difficult and slow as a result of the compact layers of basalt, a borehole may be preferable due to relative ease of construction.

On the basement complex, transmissivity and storativity of the shallow weathered aquifer and the deeper fractured bedrock aquifer are shown to vary (Table 5.3). At some locations the bedrock aquifer has a high transmissivity and provides significant yields, as recorded at the existing community boreholes at sites 1 and 3. At other locations the bedrock aquifer has a relatively low transmissivity; poor community boreholes at sites 4 and 5 highlight this problem. In general, yields from project deep exploratory boreholes were higher than from existing community boreholes especially where the weathered zone was screened rather than cased. This has important implications. It suggests a) that siting boreholes by exploratory drilling in the shallow regolith may be a good method, helping to overcome the variability found in productivity of the deep aquifer, and b) that boreholes in this region would be better if screened in the regolith rather than cased (site 5 is a case in point).

It is also important to note that yields predicted for all large-diameter and collector wells are more consistent than borehole yields and are adequate for small scale vegetable production.

## **5.6 Findings of the comparison of well types**

This chapter has concentrated on the sustainability of yield as a criteria within the choice of well type. The description of a series of pumping-tests carried out on the well types have highlighted the inappropriateness of traditional analysis methods. The difficulty in analysing pumping-tests in crystalline basement is the vertical and laterally variability. The investigations needed to obtain required data for input to more sophisticated models for analysis are difficult and time-consuming and certainly beyond the scope of a development organisation. With these qualifications in mind a series of pumping-tests were carried out and the results analysed. Though the results may not be totally accurate they are indicative of the performance of each well type. It is important, however to remember that this study is of a very small sample though the authors are not aware of any other similar study having been undertaken.

The main conclusions from this study are:-

1. Deep exploratory boreholes sited by identifying the area underlain by the thickest weathered zone consistently gave the highest yields (sample of 3).
2. Where boreholes are suitably screened within the weathered zone, yields can be substantially higher.
3. A consistently adequate supply of water for domestic use and irrigation was obtained from the shallow weathered aquifer, both by large-diameter wells (18 m<sup>3</sup>/day, on average) and collector wells (26 m<sup>3</sup>/day, on average).
4. The increase in the sustainable yield due to the conversion of a large-diameter well to a collector well is variable, but on average is significant, 38%. Where the demand for water is expected to be relatively high (approximately 25 m<sup>3</sup>/day) it may be cost-effective to carry-out the conversion (Lovell *et al.*, 1996).
5. The security of a number of pumps at one location, whether they are attached to one well or more than one borehole is a great advantage as when one pump breaks there are others still available. This increases the chances of a continuous supply of water. It is likely, however, that handpumps placed in boreholes will have a higher probability of breaking. This is due to the greater height over which they have to lift water and the extra weight on bearings from the rising main, pump rods and the longer column of water. Maintenance will also be more difficult for local people to carry-out with the added weight of pump and fittings.

## 6. DISCUSSION

Although crystalline basement rocks have low storage compared with many other aquifer types, the volume of water held during 'normal periods of recharge' is large relative to the levels of abstraction required by rural communities of much of Africa. As mentioned previously Wright (1992) has estimated that a volume of water equivalent to only 1-3 mm/a of groundwater recharge would be necessary to provide an adequate supply of water to the population of Africa. As an example, using figures obtained from the Romwe Catchment study, a simple water balance for a well shows that a sustained yearly abstraction of 2500 m<sup>3</sup> can be obtained from a cylinder of shallow weathered aquifer of a radius of only 225 m (this assumes a uniform fluctuation in the groundwater-level in the aquifer of 4 m, an aquifer storage of 0.4% and recharge of 16 mm/a). However, though sufficient water may be available within the basement-aquifer in the longer term it has been shown within the studies reported here that temporal and spatial variation in groundwater recharge and aquifer permeability are still major controls on the sustainability of yield from wells and boreholes in the short and medium term (<15 years).

The manifestation of a lack of sustainability of yield is a serious decline in well water-levels. Ignoring well interference and well effects, water-level decline in wells and boreholes can be split into two components: the regional fall in water-levels due to the natural lateral flow of groundwater down-gradient; and the localised dewatering of the aquifer around abstraction points. Low groundwater recharge will not allow regional water-levels to recover at the end of the dry season; low aquifer permeability causes steep cones of depression to develop around pumping wells and boreholes. In some areas, as shown in the Romwe Catchment, these steep cones of depression can result in wells drying-up over the period of a dry season. Elsewhere, though localised drawdown is not a problem normally, the combination of lower permeability and extended periods of low recharge may result in restricted levels of abstraction in the medium term. Though the buffering nature of groundwater storage can cope with drought years, when this is superimposed on extended low recharge periods, as occurred in Zimbabwe in 1991/92, the impact can be devastating. In drought years, the requirement for water from groundwater sources is significantly increased as alternative sources of water such as rainfall collectors and rivers can be significantly reduced and as more supplementary irrigation of crops and vegetables may be necessary.

The factors important to the two controls, groundwater recharge and aquifer permeability, and the relevant management options for improving the provision of sustainable groundwater supplies are discussed in the following sections. Much of the discussion draws on the results from Chapters 4 and 5. (Nb. As already stated, this project has restricted itself to the study of sustainability of yield, it therefore has not addressed water quality issues and has only briefly addressed sociological problems.)

### 6.1 Groundwater recharge

#### 6.1.1 Controls on groundwater recharge

Examples from the Romwe Catchment illustrate the temporal and spatial controls on groundwater recharge.

##### *Soil type and land use*

The flat cultivated region within the Romwe catchment has two areas of differing soil cover, roughly separated by the stream bed. The grey soils on the southern side of the valley are less coherent and more likely therefore to collapse and form a flat surface that crusts. This reduces recharge and enhances runoff which can cause gullying and soil erosion to occur (Butterworth *et al.*, 1995). The red soils on the northern side suffer from the same problems but to a lesser degree as the soil is more coherent and therefore rougher which reduces runoff and increases infiltration. The cultivation of land is the reason for the soil being bare, where natural vegetation is present runoff will be less but evapotranspiration is likely to be greater than in

cropped areas. In addition, the herding of livestock on land will also cause soil to become compact and runoff to be enhanced.

### ***Weathered zone profile***

The shallow weathered zone of crystalline basement rock can be sub-divided into three layers: the surface soils and collapsed zone; the upper saprolite; and the lower saprolite. The surface layer often has high permeability relative to the underlying upper saprolite. Where the upper saprolite is thick this low permeable layer can severely restrict the recharge to the deeper aquifer and can cause significant lateral flow (interflow). At Romwe the weathered zone produced from the leucocratic gneisses has a significantly greater thickness of clayey upper saprolite. As shown by estimates from the chloride balance, the resulting recharge is low, approximately a third of the recharge to the aquifer with the higher concentration of mafic minerals.

### ***Rainfall quantity and pattern***

Results from the Romwe catchment have shown that groundwater recharge is dependent both on the quantity of rainfall and the distribution (Butterworth *et al.*, 1995). This affects the ability to overcome the soil moisture deficit. In 1993/94 the main recharge took place subsequent to a major rainfall event. In the early part of the 1994/95 wet season though rainfall was not below average, it was well-distributed and as a result recharge was insignificant. Although subsequent recharge did take place in response to a major rainfall event, the overall rise in groundwater levels was below that of previous monitored years even though the annual rainfall total was higher. Further, the proportion of rainfall that infiltrated was reduced more on the southern side of the catchment.

#### ***6.1.2 Options for improvement***

There is no control on rainfall quantity and distribution and therefore to a large degree the populations inhabiting arid and semi-arid regions are at the mercy of an unreliable climate. Options do exist, however, for increasing the proportion of rainfall that recharges aquifers. The effectiveness of artificial recharge installations are doubtful, as shown by the experimental site at Romwe. The best method would appear to be through the use of improved land management practices. These include: conservation tillage; construction or improvement of contour bunds; and better control of grazing. This aspect is a major theme of the work being carried out by IH and DRSS in the Romwe Catchment.

## **6.2 Aquifer permeability**

### ***6.2.1 Controls on aquifer permeability***

#### ***Shallow weathered aquifer***

The typical profile produced from the weathering of basement rocks is shown in Figure 2.1. The overall permeability of the weathered zone is dependent on the nature of the weathered material and the thicknesses of the component layers. The upper saprolite has a relatively low permeability due to the high proportion of secondary clay minerals; the basal zone of the lower saprolite at the top of the saprock has a relatively high permeability as it retains the texture and primary porosity of the parent rock. A deep overall weathered layer and a shallow water-table produces a significant thickness of the saturated aquifer which correlates with greater well and borehole yields.

The controls on the degree and nature of the weathering of crystalline basement rock are many, as described in chapter 2. These include parent rock geology, the age of the erosion surface, relief and the climate, past and present. The spatial variability of the shallow aquifer can therefore be great. In the Romwe catchment the weathering of the rock with the higher content of mafic minerals (on the northern side) has resulted in a more transmissive material which allows greater levels of recharge and shallower cones of depression around

abstracting wells. The dominant mineral assemblage underlying the southern side of the catchment has caused a greater thickness of the low transmissivity upper saprolite to develop. This results in the development of steep cones of depression around wells that are significant enough to cause the wells to dry-up during the period of a dry season, even following a normal rainfall period.

#### ***Deep bedrock aquifer***

The permeability of the deep bedrock aquifer is dependent on fractures and linearities. If fractures form a significant network and can tap the storage of the weathered layer, boreholes will be high yielding. The yield from boreholes in bedrock are greater where the thickness of the saturated weathered layer is significant. Where linearities such as dykes and quartz stringers exist preferential weathering takes place that can produce local high transmissivity zones. However, the bedrock aquifer like the weathered zone is spatially variable and without expertise to locate linearities the siting of high yielding and sustainable boreholes can be difficult.

#### **6.2.2 Options for improvement**

There are two main options for increasing the sustainability of yield from sources in basement aquifers: improved well siting and well design.

#### ***Well and borehole siting***

Well and borehole siting has not been explored in great depth in this project. The siting of the collector wells for the "small scale irrigation" project was based on regional geology and sociological criteria and was very much village based. Within the vicinity of the village chosen, the wells were sited by exploratory drilling to locate the thickest zone of the saturated weathered layer (Lovell *et al.*, 1996). This method has proved successful and it is doubtful whether any geophysical method would have been as cost-effective.

The difficulty of regional geophysical programmes to identify linearities is that they are both expensive and do not necessarily find sources of water convenient to villages that are in need. One important result of the Romwe study is the correlation of well productivity with small-scale variations in the mineralogy of the parent rock that cause differing weathered zone profiles. These small-scale variations can be identified from remote sensing images. It is suggested that remote sensing could therefore be used to identify areas of greatest potential for borehole and dugwell siting in the vicinity of villages. The method has particular relevance in high-grade metamorphic regions where the variations in mineralogy are most significant. It is recommended that further research be undertaken to test the correlation.

#### ***Well type***

The choice of well type for a site depends on the aquifer make-up. For example, where the shallow weathered zone is thin (<10 m) or the water-table deep, a borehole may be the only option. The results of the comparison of well types in Chapter 5 though specific to the post-African erosional surface of south-east Zimbabwe, did raise some points of general relevance.

The results suggested that saturated thickness of weathered zone was a good criterion for locating both dug well and borehole. They also showed that a significant improvement could be made on the performance of boreholes if they were screened in the weathered zone. The modelled sustainable yields for large-diameter wells constructed in the shallow weathered layer showed consistently that adequate yields for village water supply could be obtained. The improvement made to these wells by the conversion to collector wells though variable was, on the whole, significant and is a viable option where greater water supplies are required for supplementary irrigation. Collector wells will lengthen the period over which abstraction can continue during extended periods of low recharge and drought.

Other aspects related to the sustainability of a groundwater scheme, favoured the choice of large-diameter wells or collector wells completed in the weathered zone. The sense of ownership of communities who are



involved with the digging of their own well improves the likelihood that responsibility for the upkeep of the well and the maintenance of the pumps will be assumed. The ability to attach more than one pump to a large-diameter well will mean there is a backup if a pump fails. The option exists to drill more than one borehole but pump failure is also more likely in boreholes. The low storage of boreholes cause greater water-level drawdown which in turn causes more strain on the pump required to lift the water over a greater height. The weight of the extra rods required will also cause additional strain. The advantage of boreholes is the ease of construction.

## 7. CONCLUSIONS

This report has documented a study that has been undertaken to review and investigate further the controls on the sustainability of yield of wells and boreholes in crystalline basement aquifers. It has highlighted aquifer permeability and groundwater recharge as the major controls. Low permeability can cause significant localised dewatering around wells, which on its own, or combined with extended periods of low recharge, can cause a serious decline in well yields. This can be devastating during drought years when the groundwater stored is an even more important and more heavily exploited source of water for rural populations in arid and semi-arid regions.

The Romwe Catchment study has shown that the weathered profile of the basement rock has a strong control on the yield that can be obtained from shallow traditional wells. The nature of the weathering determines the permeability of the shallow aquifer which controls the shape of the water-table in the locality of a pumping well. Where permeability is particularly low the period over which water can be abstracted even in a normal year can sometimes be less than one dry season. In the small area of the Romwe Catchment, differences in the mineralogy of the parent rock and subsequent variations in the weathering profile are sufficient to make the sustainability of yield of wells significantly different. The variations in parent rock mineralogy also control the soil type which, along with the shallow weathered zone profile, determines the level of groundwater recharge.

A number of development options to improve sustainability are put forward as a result of this project and the ongoing associated work in south-east Zimbabwe (Lovell *et al.*, 1996, Butterworth *et al.*, 1995). Land management techniques could be implemented to increase the amount of groundwater recharge in the long-term. Research into the merit of various measures is being undertaken in the Romwe Catchment at present by IH and DRSS. This report, however, has highlighted that in low permeability aquifers the overriding factor for lack of sustainability in yield is the localised dewatering of the aquifer that takes place in the vicinity of the source. In these environments the siting and design of the well or borehole are the important issues.

Lovell *et al.* (1996) have suggested siting using exploratory drilling to identify areas of optimal saturated thickness of weathered basement could be successful. This is the case both for wells and boreholes. They also suggest that the screening of boreholes in the weathered zone may improve yields significantly.

Where saturated thickness of weathered zone is sufficient (>10 m) modelling has indicated that the large-diameter dugwell and the collector well give consistently adequate sustainable yields for village supplies, with a provision for small scale irrigation of allotment type gardens. These well designs could be the best option for groundwater development in low permeability aquifers particularly where the use of geophysical surveying is not possible.

A technique for well siting using remote sensing to identify areas of preferential weathering via soil type has been devised and has been put forward to ODA for further research.

## 8. RECOMMENDATIONS

- continue monitoring all components of the hydrological cycle within the Romwe catchment and initiate other such studies in catchments representative of the different physical settings found in the region (eg granites, basalts, Kalahari sands).
- continue research in instrumented catchments into the development and application of improved land management techniques.
- develop the well siting technique that uses remote sensing to identify areas with weathering preferential for siting dug wells and boreholes.
- assess the method for borehole siting by exploratory drilling, using thickness of saturated weathered zone as the criteria.
- promote the development of the shallow aquifer for groundwater using large-diameter wells and collector wells.
- promote the screening of boreholes in the weathered zone.
- refine the methodology that uses exploratory borehole tests to indicate the most suitable well or borehole type for a site; and for testing large-diameter wells to determine if it is necessary to convert them to collector wells.

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