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Hydrological processes and water resources management in a dryland environment III: Groundwater recharge and recession in a shallow weathered aquifer

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Abstract

In crystalline basement regions of Africa, shallow weathered aquifers provide vital water resources for rural communities. To quantify evidence of the behaviour of these shallow aquifers, groundwater levels were observed at a network of 65 boreholes within the Romwe Catchment in southern Zimbabwe. Soil moisture was monitored at selected sites.

Groundwater hydrographs showed considerable spatial and temporal variation. Where the soil profile was freely draining, groundwater levels typically responded within a few days of major rainstorms and large annual fluctuations in the water table of up to 7 m were recorded. In areas where a thick clay layer exists, annual fluctuations were smaller and groundwater levels rose more gradually in response to rainfall. In cultivated areas, vertical drainage was an important recharge mechanism. Groundwater hydrographs typically have an exponential recession and, by the end of the dry season in the years studied, levels were close to the base of the weathered aquifer. Variations in hydrograph response between years illustrate the importance of rainfall amount, intensity and distribution on groundwater recharge.

Introduction

Crystalline basement aquifers are commonly classed as two layer systems, with a shallow weathered layer overlying fractured bedrock (Chilton and Foster, 1995). The fractured bedrock is exploited by boreholes, typically 50–80 m in depth and often cased in the weathered layer. The shallow weathered aquifers have traditionally been a vital source of water for rural communities (Wright, 1992), exploited by hand-dug wells, typically 1–1.2 m in diameter. The depth of these wells is constrained by the depth of weathering, which in southern Zimbabwe is often up to 15 m. Weathering is dependent on many factors, including the texture and mineralogy of the underlying parent rock, topography and climate. There may be significant lateral variability both in the depth and the nature of the weathering profile which in turn controls the depth to the saturated zone and aquifer permeability.

In Zimbabwe, shallow weathered aquifers are currently the focus of increased development for both domestic water needs and small-scale irrigation (Lovell *et al.*, 1996). Elsewhere in Africa, these aquifers may hold the key to future resource development (Howard and Karundu, 1992). However, the relatively little quantitative evidence of the long-term behaviour of these aquifers hampers evaluation of the sustainability of water supply schemes based on such aquifers, and the appropriate development of future groundwater exploitation. In particular, the influence on aquifer recharge of variations in rainfall and patterns of land use around water-points is unclear. Natural resource management initiatives require an improved understanding of aquifer and recharge characteristics in areas where groundwater is important.

In this paper, characteristics of the observed groundwater level fluctuations from a dense network of boreholes in a small dryland catchment in southern Zimbabwe are presented. The implications of these observations for management of groundwater resources in similar areas are considered.

Materials and Methods

STUDY SITE

The description and instrumentation of the 4.6 km^2 Romwe catchment, located in southern Zimbabwe, 86 km south of Masvingo (20° 45′ S, 30° 46′ E), is given by Bromley *et al.* (1999). Land use includes rainfed cultivation on the valley floor and miombo woodland on the surrounding hillslopes (Fig. 1). Rainfall is strongly seasonal; on average 84% is received in the summer rainy season between November and March. Average annual rainfall at Chendebvu Dam, 12 km from the catchment, was 585 mm for the period 1952–93. The 1950s were generally wet, the 1960s relatively dry, the 1970s wet and the 1980s and early 1990s dry.

A series of basement complex gneisses underlies the catchment. Folds, fractures and faults are widespread, some of which are intruded by dolerite dykes. Major geological units are pyroxene gneiss (dark-coloured and rich in ferro-magnesian minerals such as pyroxene, mica and amphibole), quartzo feldspathic granulite (lighter-coloured and composed mainly of feldspar and quartz) and between these two extremes, leucocratic pyroxene gneiss. Generally, the pyroxene gneisses are more easily weathered and less resistant than the leucocratic pyroxene gneisses or quartzo-feldspathic granulites. The shallow weathered aquifer occurs in the low-lying valley floor of the catchment. The two most important soil types in this zone are red clay soils associated with the pyroxene gneiss, and grey duplex soils of sandy loams over sandy clay where the leucocratic pyroxene gneiss crops out. The red clay soils tend to be freely draining, while the grey duplex soils are prone to the formation of a perched water table and interflow in wet years.

GROUNDWATER LEVELS

Groundwater levels were measured at 65 observation boreholes located in and around the catchment (Fig. 1). Where the leucocratic pyroxene gneiss occurs in the southern part of the catchment (Bromley *et al.*, 1999), depth to bedrock at the boreholes averaged 7.0 m. On the northern side in areas of pyroxene gneiss, average bedrock depth was 10.3 m. Groundwater levels were recorded weekly, with additional readings taken daily for 5 days after rainstorms exceeding 20 mm. At some sites, monitoring commenced in 1992, while at others it started in late 1993; thus, depending on location, data are available for three or four wet seasons.

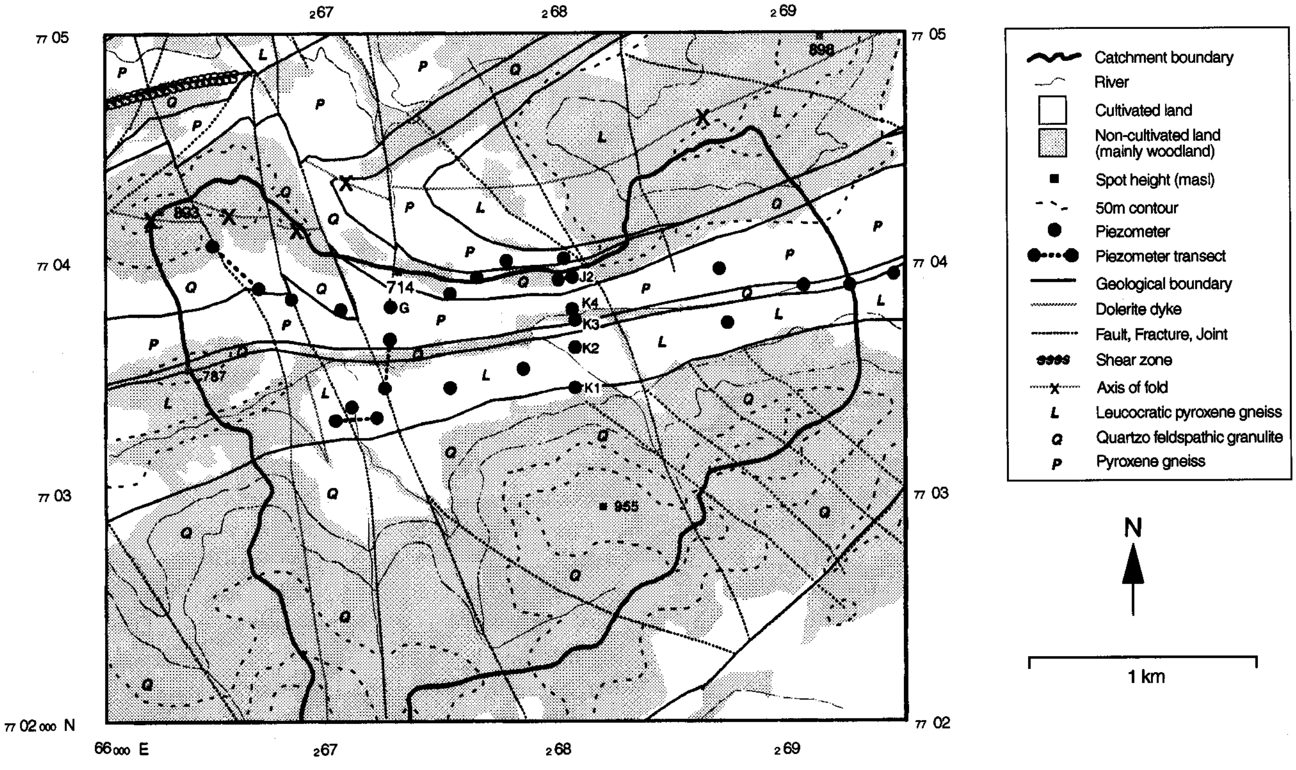


Fig. 1. *Catchment geology and monitoring sites.*

RAINFALL

Rainfall was measured at the study site from November 1993, and eventually encompassed 13 sites, including a tipping-bucket raingauge installed at ground-level with an anti-splash grid. Historical daily rainfall records dating from 1953 were obtained for the Meteorological Department rainfall station at Chendebvu Dam. All rainfall data were corrected to equivalent ground level rainfall using relationships determined at the study site between gauge type, installation height and rainfall catch (Butterworth, 1997).

SOIL WATER MEASUREMENTS

In-situ soil water measurements were made using a neutron probe (Didcot Instruments, UK) and other techniques (Bromley *et al.*, 1999). In this paper, reference is made to measurements from a grid of 24 sites on the red clay soils (Red sub-catchment), a grid of 23 sites on the grey duplex soils (Grey sub-catchment) and a transect of 6 sites, again on red clay soils (Inselberg hillslope transect). Along the inselberg hillslope transect shown in Fig. 2, both soil and ground-water measurements were made at each site, an access tube being located within 2 m of the observation borehole. Estimates of drainage from the grid of sites on the red clay soils were available from analysis of soil water content changes and soil hydraulic potential profiles measured using tensiometers, using the Zero Flux Plane method (Butterworth, 1997).

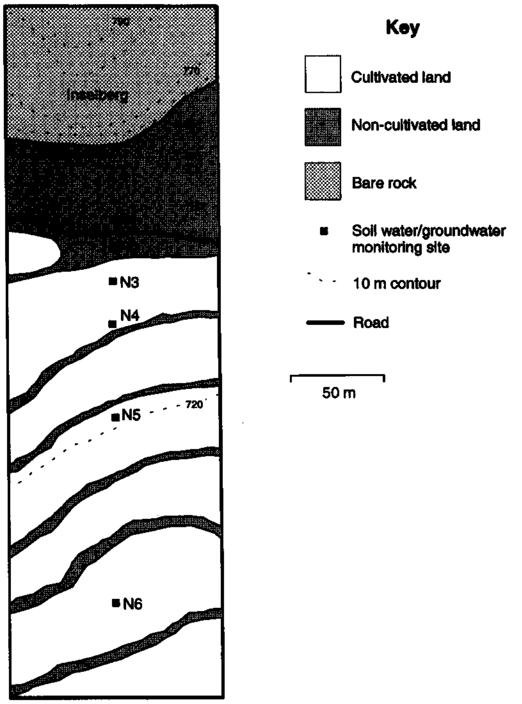


Fig. 2. *Monitoring sites along the inselberg hillslope transect.*

Results and discussion

GROUNDWATER RECHARGE AND RECESSION

Considerable spatial variation in groundwater level response was observed within the catchment. In the northern part of the catchment where pyroxene gneisses predominate, and particularly towards the western end, levels respond rapidly to rainfall within a few days of major rainstorms. In the southern part of the catchment where leucocratic gneisses occur, levels rise much more gradually. Groundwater hydrographs from sites typical of these two areas are shown in Fig. 3. At site G in the north-eastern part of the catchment, groundwater levels rise much more rapidly than at site K2 in the southern part of the catchment. At site G, the red clay soils are relatively permeable despite the high clay content, as a consequence of the well-developed micro-granular soil structure. At site K2, a thick sandy clay layer exists below the coarser surface soil horizons. This layer, much less permeable, impedes recharge of the weathered aquifer below. In wetter years, a perched water table forms in the upper soil horizons above the sandy clay layer and considerable interflow at the interface results.

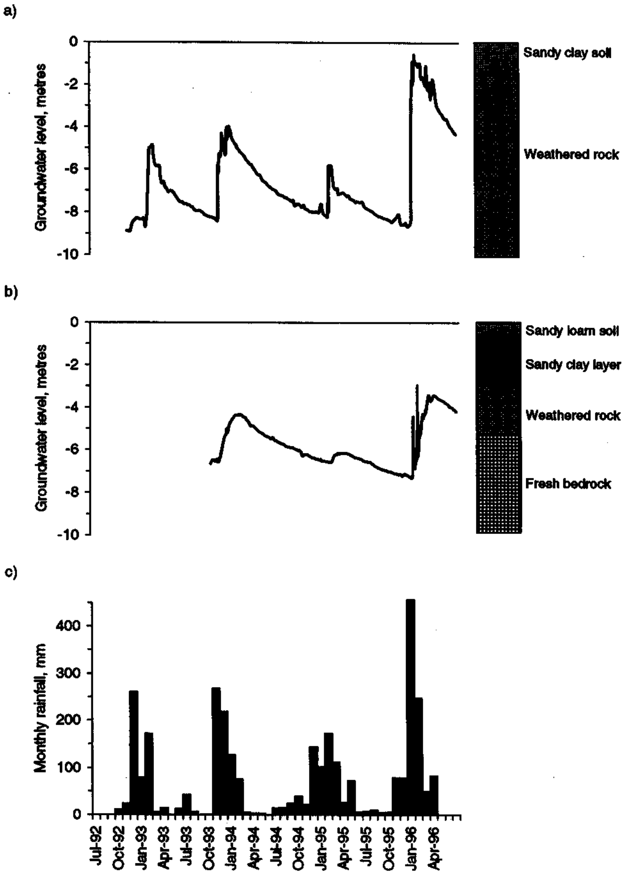
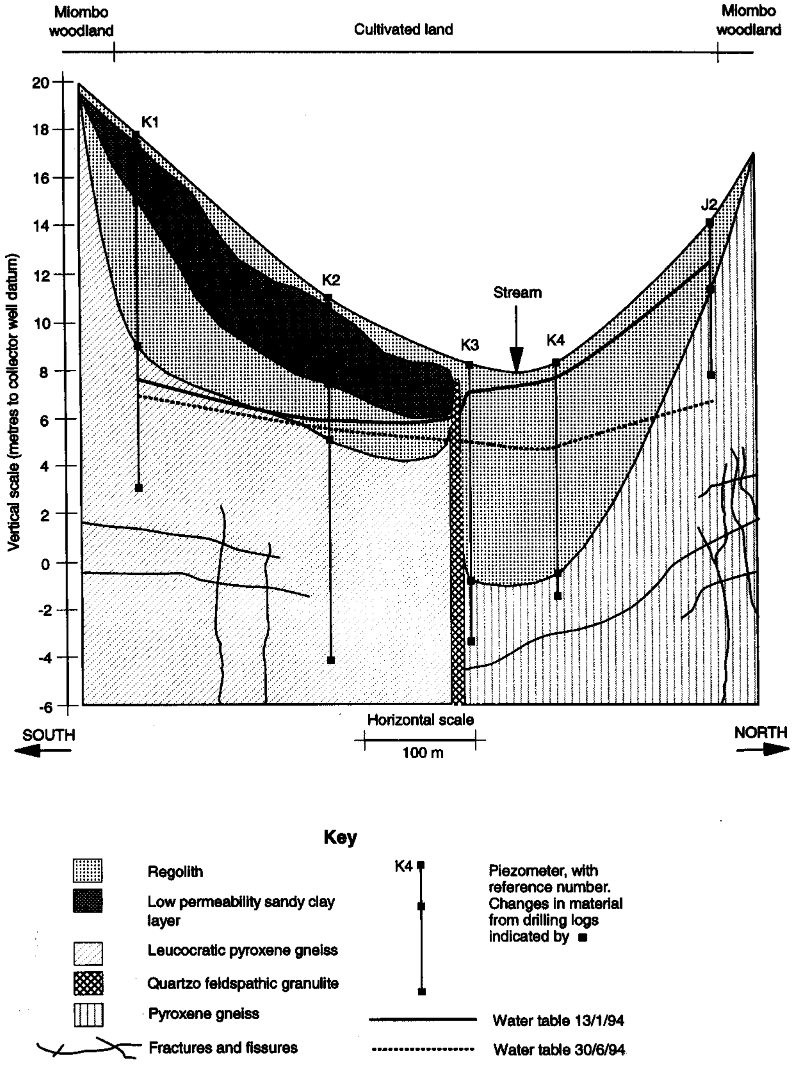


Fig. 3. *Groundwater level hydrographs at two sites a) observation borehole G, b) observation borehole K2 and c) monthly rainfall totals.*

A cross-section across the catchment constructed from borehole drilling logs is shown in Fig. 4. Water levels in 1993/94 at times of generally high levels (13 January 1994) and low levels (30 June 1994) are shown. The limited fluctuation in levels (less than 3 m) in the weathered aquifer on the southern side of the catchment below the sandy clay layer, contrasts with the larger fluctuations of up to 7 metres in the northern part. The most productive traditional wells and the high yielding collector well have all been sited in the northern part of the catchment. The good well performance in this area is attributed to: increased recharge, the greater degree of weathering, the influence of faults and fractures and the retention of groundwater behind the band of quartzo feldspathic gneiss running approximately east-west along the line of the main stream.

The recession in groundwater levels is typically exponential, as Bredenkamp *et al.* (1995) observed for various aquifers in South Africa. Over the dry season between April and September, levels generally fell close to the base of the weathered aquifer and relatively little recharge was carried over to subsequent years. While possible causes are uptake by deep rooting vegetation, abstraction from wells, lateral groundwater flow or leakage into the fractured bedrock aquifer, the major causes are probably vegetation uptake and lateral groundwater flow. About 0.31 km^2 of the valley floor is covered by deep rooted and often evergreen species along drainage lines. Although transmissivity is generally considered to be low in crystalline basement aquifers, a more transmissive layer generally occurs at the base of the regolith (Wright, 1992; Macdonald *et al.*, 1995) and, within the catchment, there



Note: Water level estimated at J2 on 30/6/94 when piezometer was dry.

Fig. 4. *Cross-section across valley showing depth of weathering and zone of water table fluctuation.*

can be a large east-west gradient in groundwater levels. At the end of the dry season in November 1993, the gradient in levels was in excess of 60 metres over a distance of 2.75 kilometres, a slope of 2.2%. Human abstraction of groundwater is small, equivalent to less than 1 mm across the catchment.

The complex hydrogeology means that it is essential for wells and boreholes to be carefully sited. To obtain reliable yields it is important to locate: firstly, the maximum depth of saturated aquifer thus minimising the effect of the natural recession in groundwater levels: and secondly, an aquifer of reasonable permeability to avoid failure through the formation of a steep cone of depression around the well.

RAINFALL AND GROUNDWATER RECHARGE

Although hydrograph shape seems relatively consistent over time, the magnitudes of groundwater rise observed in the four rainy seasons since 1992 were markedly different. Annual rainfall and the maximum rise in groundwater levels during these seasons are shown in Table 1. Rainfall of 569 mm in the 1992/93 season was only 81% of the estimated long term average rainfall of 704 mm (corrected to ground-level rainfall). In comparison, annual totals of 740 and 738 mm in 1993/94 and 1994/95 respectively, were 105% of long-term mean rainfall.

For the smaller sample of sites near the collector well, where water level measurements were available from 1992, the average maximum rise in groundwater level in 1992/93 was 2.06 m compared to 2.81 m in 1993/94 and 0.64 m in 1994/95.

For the larger sample of sites with records from 1993, the average maximum rise in 1993/94 was 2.72 m. This is again considerably greater than the 1.09 m in 1994/95 when a similar amount of rainfall was received. The major difference in rainfall between the 1993/94 and 1994/95 seasons was not the total amount, but the distribution of rainstorms. In the 1993/94 season, rainfall distribution was skewed towards the early part of the rainy season and the largest monthly rainfall total was recorded in November. In 1994/95, the rainfall was distributed over a longer period and skewed towards the latter part of the season, with the largest monthly rainfall recorded in February. At some sites there was no rise at all in groundwater levels during this season. Even in a year of above average rainfall, recharge may be low or negligible if the distribution of rainfall is not favourable. The intensity of rainfall is also important because of runoff generation and the effects of surface redistribution of rainfall due to runoff and runon during rainstorms (Butterworth *et al.*, 1999a).

Table 1. Annual rainfall and mean groundwater level rise

Season	Rainfall[1], mm	Mean groundwater level rise, m	
		Collector well observation boreholes	All sites
1992/93	569	2.06	
1993/94	740	2.81	2.72
1994/95	738	0.64	1.09

[1] Corrected to ground-level gauge.

More detailed information on the relationships between rainfall and recharge in the catchment can be observed from the amount of rainfall required to induce the first groundwater level response in any year. In 1993/94, groundwater level rises were initiated by 153 mm of rainfall over a 7 day period from 24–30 November 1993 including 96 mm on a single day. These were the first significant rains of the season and, therefore, occurred when soil water deficits were at maximum levels after the long dry season. In 1994/95, groundwater level responded at most sites to 141 mm rainfall received in a single storm on 17/18 February 1995, after a dry period of 27 days during which only 24 mm rainfall was received and so large soil water deficits had accumulated. In 1995/96, groundwater levels rose on 18 January 1996 after 162 mm rain during the period 14–17 January 1996. This followed a dry period of 23 days during which only 3.5 mm rain was received, after moderate rains in mid December 1995. Observations during these three years, therefore, show that rainfall of between 141 and 162 mm during a period of up to 7 days resulted in widespread groundwater recharge.

Rainfall events which did not result in groundwater level rises in most parts of the catchment included, in 1994/95, 57 mm (3 days), 76 mm (5 days) and 91 mm (5 days) and in 1995/96, 61 mm (2 days) and 53 mm (5 days).

In considering the factors required to generate a groundwater level rise, variations in antecedent soil water deficits, runoff and surface redistribution of rainfall will all be important in addition to the amount of rainfall. However, the above evidence from a limited study period of three rainy seasons, suggests that rainfall exceeding about 100–140 mm during a short period of up to a week will result in widespread recharge to groundwater. Modelling studies which compared simulated drainage and maximum weekly rainfall over the period 1953–96, generally support this observation (Butterworth *et al.*, 1999b). Over this 43 year period, significant drainage would have occured in only 2 years following a maximum weekly rainfall below 100 mm and, in all but one year, when maximum weekly rainfall exceeded 140 mm.

SOIL WATER MOVEMENT AND GROUNDWATER RECHARGE

The relatively rapid response of groundwater to rainstorms, with levels at many locations rising only a few days after rainfall, raises important questions about the processes responsible for groundwater recharge. The most rapid responses were observed along the inselberg hillslope transect (Fig. 2) which has red clay soils and where groundwater hydrographs were particularly ‘flashy’. Combined measurements of soil moisture contents and groundwater levels made at this site from February 1994 were analysed to compare responses in the unsaturated and saturated zones.

Deep soil moisture storage, and groundwater levels along the inselberg hillslope transect are shown in Fig. 5, together with monthly rainfall totals. Soil moisture storage is shown as the total amount of water stored between 1.3–2.1 m depth, with the exception of site N3 where limited tube depth permitted measurement only to 1.9 m. At this depth, in fields cropped mainly with maize, the amount of water extracted by plants is likely to be small or negligible (Butterworth, 1997). However, at site N2 deep rooting trees and shrubs close to the access tube, mean that it is unreasonable to assume that extraction of water by plants from this layer is small.

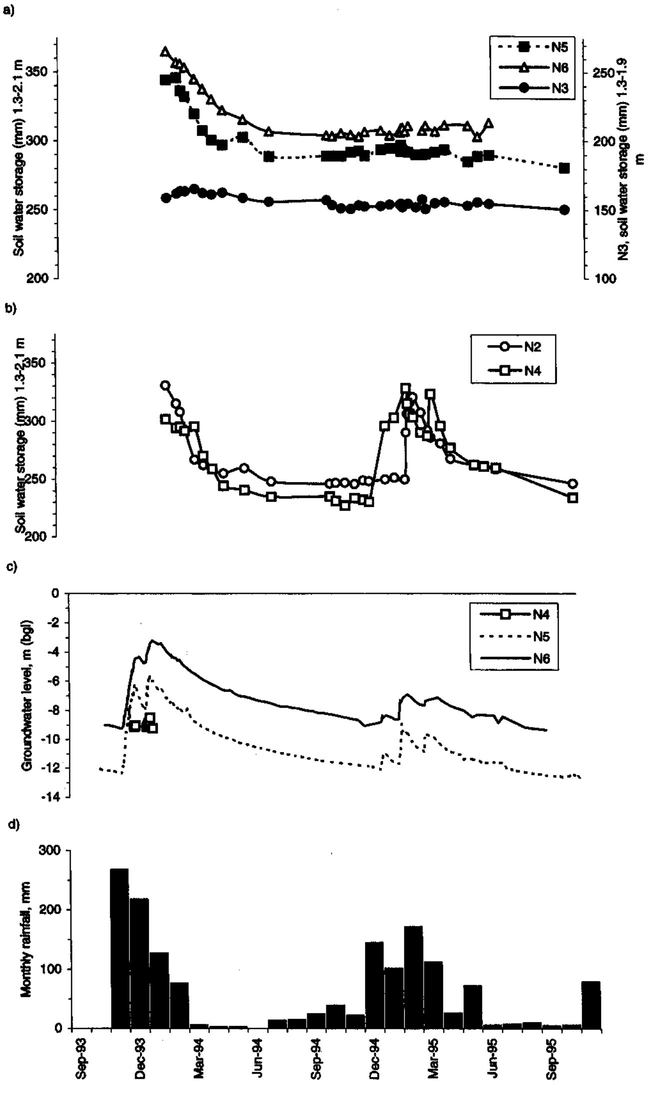


Fig. 5. *Inselberg hillslope transect hydrology, Sep 1993 to Nov 1995, a) soil water contents, sites N3, N5 and N6, b) soil water contents, sites N2 and N4, c) groundwater levels and d) monthly rainfall.*

In the 1994/95 season, significant fluctuations in deep soil moisture contents occurred at only two sites (N2 and N4) where run-on was shown to have resulted in enhanced infiltration (Butterworth, 1997). In the previous 1993/94 season, large fluctuations are indicated at four of the five sites with only a small fluctuation at site N3. These observations suggest that drainage from the soil profile occurred over larger areas during the 1993/94 season than in 1994/95. In 1993/94, concentrated rainfall early in the season overcame soil moisture deficits at most sites and initiated drainage. In 1994/95, drainage was initiated only at sites where surface redistribution of water resulted in enhanced infiltration. During these two years, groundwater was observed within the depth of the observation boreholes only at sites N5 and N6. Although recharge did occur at both these sites, with a groundwater response to rainstorms in mid-January, mid-February and late March, 1985, wetting of the lower soil profile at these locations did not occur. At sites N5 and N6, located just below and in the middle of a field respectively, the source of recharge was therefore not in the immediate vicinity of the borehole.

Hence, recharge along the hillslope may occur at sites of enhanced infiltration due to surface redistribution of rainfall within fields, such as at sites N2 and N4 located just above contour bunds. For the period in which groundwater levels responded to rainfall in the 1994/95 season, soil moisture contents at the base of the monitored profiles at sites N2 and N4 and groundwater levels at sites N5 and N6 are shown in Fig. 6. Groundwater levels rose at both sites by around one metre during the week after the 16 January 1995 rainstorm. Although deep soil water contents at site N2 did not change significantly due to this rainfall, there was wetting at 2 m depth at site N4. Larger rises in groundwater levels, up to 3 metres, followed the 17/18 February 1995 rainstorm. Further wetting of the soil profile was observed at site N4 following this event and an increase in soil water content at 2.2 m was observed at site N2. Rainfall in late March resulted in further increases in soil water content at site N4 but not at site N2.

The soil water evidence shows that, coincident with groundwater level responses, there was wetting and therefore drainage to a depth of at least 2 m at two in-field sites along the hillslope. The subsequent movement of soil water through the entire unsaturated zone, to depths of up to 12 metres, was not studied. However, drainage at 2 m is strong evidence that significant drainage within fields is a component of, if not entirely responsible for, groundwater recharge even in areas where the response is very rapid. Alternative additional loci for recharge may be at the base of the inselberg which generates large volumes of runoff.

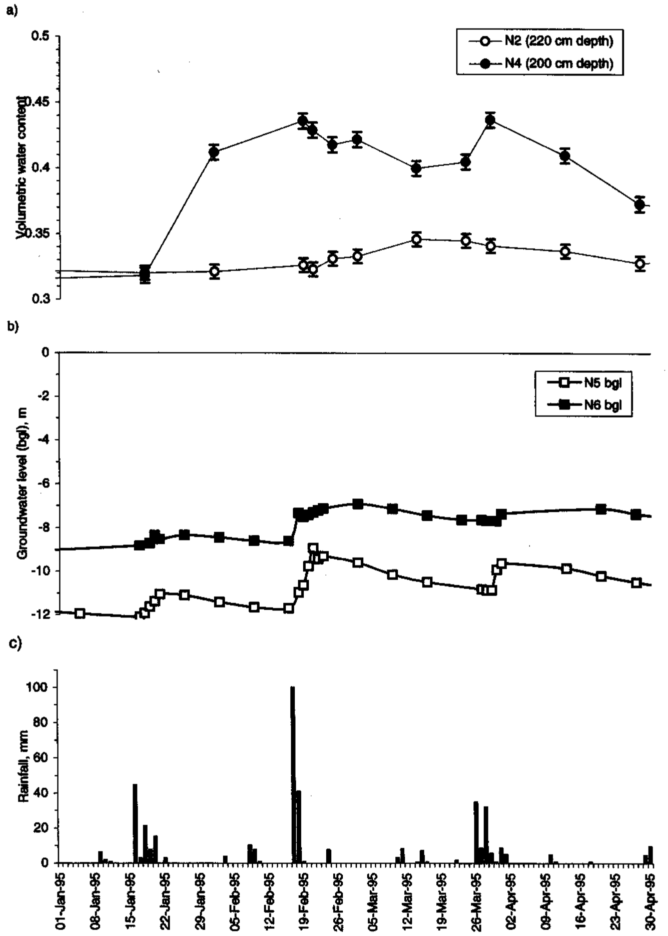


Fig. 6. *Comparison of deep soil water content fluctuations and groundwater level response along the inselberg hillslope transect, 1994/95 rainy season a) soil water content of deepest monitored layer, b) groundwater levels and c) daily rainfall.*

Conclusions

1) Groundwater recharge has been shown to be strongly controlled by the variable characteristics of the weathering profile. In particular, recharge was relatively low in areas with a thick sandy clay layer in zones of leucocratic pyroxene gneiss. Higher recharge in areas with more freely draining soils, derived from pyroxene gneiss, resulted in annual fluctuations in groundwater levels of up to 7 metres.

2) Groundwater levels recess rapidly over the dry season, often close to the base of the weathered aquifer, before recharge occurs in the following rainy season. This means that wells tapping only the weathered aquifer may fail if recharge does not occur in a particular year. Measures to ensure that recharge occurs in all years, such as bunds designed to encourage infiltration around wells, are desirable. Good well siting can also reduce the risks of failure.

3) Groundwater recharge is affected by the distribution and not just the amount of rainfall that occurs in a year. In particular, for widespread recharge, observations as well as modelling suggest a rainfall of 100–140 mm within one week is necessary.

4) Soil water measurements showed that at least a component of the rapid recharge to the shallow weathered aquifer was due to drainage within cultivated areas, although in years with evenly distributed rainfall this was observed only up-slope of contour bunds where surface water was concentrated.

Acknowledgements

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References

Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J. and Janse Van Resburg, H., 1995. *Manual on quantitative estimation of groundwater recharge and aquifer storativity.* Water Research Commission Report TT73/95. Pretoria, South Africa.

Bromley, J., Butterworth, J.A., Macdonald, D.M.J., Lovell, C.J., Mharapara, I. and Batchelor, C.H., 1999. Hydrological processes and water resources management in a dryland environment I : An introduction to the Romwe Catchment Study in southern Zimbabwe. *Hydrol. Earth System Sci.*, 3, 321–332.

Butterworth, J.A., 1997. *Hydrology of a dryland catchment in southern Zimbabwe and impacts of climatic variation and land use change on shallow groundwater resources.* PhD thesis, University of Reading, UK.

Butterworth, J.A., Mugabe, F., Simmonds, L.P. and Hodnett, M.G., 1999a. Hydrological processes and water resources management in a dryland environment II: Surface redistribution of rainfall within fields. *Hydrol. Earth System Sci.*, 3, 333–343.

Butterworth, J.A., Schulze, R.E., Simmonds, L.P., Moriarty, P. and Mugabe, F. 1999b. Hydrological processes and water resources management in a dryland environment IV: Long-term groundwater level fluctuations due to variation in rainfall. *Hydrol. Earth System Sci.*, 3, 353–362.

Chilton, P.J. and Foster, S.S.D., 1995. Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa, *Hydrogeol. J.*, 3, 36–49.

Howard, K.W.F. and Karundu, J., 1992. Constraints on the exploitation of basement aquifers in East Africa—water balance implications and the role of the regolith. *J. Hydrol.*, 139, 183–196.

Lovell, C.J., Batchelor, C.H., Waughray, D.K., Semple, A.J., Mazhangara, E., Mtetwa, G., Murata, M., Brown, M.W., Dube, T., Thompson, D.M., Chilton, P.J., Macdonald, D.M.J., Conyers, D. and Mugweni, O., 1996. *Small scale irrigation project using collector wells pilot project—Zimbabwe.* Final Report: October 1992 to January 1996. Report No. ODA 95/14. Institute of Hydrology, Wallingford, UK. 106 pp.

Macdonald, D.J., Thompson, D.M. and Herbert, R., 1995. *Sustainability of yield from wells and boreholes in crystalline base-*