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Hydrological processes and water resources management in a dryland environment IV: Long-term groundwater level fluctuations due to variation in rainfall

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Abstract

To evaluate the effects of variations in rainfall on groundwater, long-term rainfall records were used to simulate groundwater levels over the period 1953-96 at an experimental catchment in south-east Zimbabwe. Two different modelling methods were adopted. Firstly, a soil water balance model (*ACRU*) simulated drainage from daily rainfall and evaporative demand; groundwater levels were predicted as a function of drainage, specific yield and water table height. Secondly, the cumulative rainfall departure method was used to model groundwater levels from monthly rainfall. Both methods simulated observed groundwater levels over the period 1992–96 successfully, and long-term simulated trends in historical levels were comparable.

Results suggest that large perturbations in groundwater levels are a normal feature of the response of a shallow aquifer to variations in rainfall. Long-term trends in groundwater levels are apparent and reflect the effect of cycles in rainfall. Average end of dry season water levels were simulated to be almost 3 m higher in the late 1970s compared to those of the early 1990s. The simulated effect of prolonged low rainfall on groundwater levels was particularly severe during the period 1981-92 with a series of low recharge years unprecedented in the earlier record. More recently, above average rainfall has resulted in generally higher groundwater levels. The modelling methods described may be applied in the development of guidelines for groundwater schemes to help ensure safe long-term yields and to predict future stress on groundwater resources in low rainfall periods; they are being developed to evaluate the effects of land use and management change on groundwater resources.

Introduction

In the early 1990s, rural communities in southern Zimbabwe experienced a series of environmental problems. Water levels in wells and boreholes began to fall, springs which had flowed since living memory started to fail and river flows became severely reduced. These trends posed a serious threat to local livelihoods. All indications pointed to the problem being linked directly to a long term decline in the regional groundwater level. There appeared to be three possible causes; changes in land use management; over-exploitation of groundwater resources; and variation in rainfall patterns. The Romwe study has shown that, in the Romwe area, the major impact is caused by variations in rainfall pattern and that the effects of land use change and groundwater abstraction are minimal.

Effects of land use change

The effects of changes in land use and land management practice on groundwater levels are complex but include two main mechanisms. Firstly, changes in vegetation type modify the uptake and hence transpiration of water by plants with trees generally consuming more water than crops or grassland vegetation (Du Toit *et al.*, 1984; Du Toit and Campbell, 1989). Secondly, the balance between rainfall and surface runoff during rainstorms is sensitive to changes at the soil surface, associated with changes in vegetation type and condition or cultivation techniques. Removal of trees reduces the amount of leaf litter at the soil surface, and overgrazing reduces the amount of near ground vegetation cover and alters the physical properties of the surface soil horizon. Consequently, infiltration rates may be considerably lower in overgrazed bare areas compared to areas where good grass cover is maintained (Cleghorn, 1966; Kelly and Walker, 1976; Du Toit and Campbell, 1989).

Although land use and land management changes may have had a significant impact on the hydrology in some parts of Zimbabwe, in the Romwe Catchment there has been little change in land use and management since settlement of the area in 1952 (Bromley *et al.*, 1999).

Effects of groundwater abstraction

Abstraction of groundwater in most communal lands, where motorised pumping is rare, is currently insufficient to lower regional groundwater levels significantly. This is certainly the case in the Romwe catchment. However, in areas of low aquifer storativity and transmissivity (Macdonald *et al.*, 1995), abstraction often results in steep cones of depression developing around wells. This may lead to failure of the water supply in the late dry season, or in drought years, but it does not cause a regional lowering of the groundwater table.

Effects of rainfall variability

In the Romwe catchment, important controls on groundwater recharge include rainfall amount, storm intensity and distribution of storms during a season (Butterworth *et al.*, 1999a). Rainfall amount and seasonal distribution are highly variable in the Lowveld area. Furthermore, consecutive periods of generally high and low rainfall have been observed in Zimbabwe (Makarau, 1996), and elsewhere in southern Africa (Tyson, 1986). The 1950s were generally wet, the 1960s relatively dry, the 1970s wet and the 1980s and early 1990s dry.

In this study, two different modelling approaches were used to reconstruct historical groundwater levels from daily rainfall records, and to evaluate the evidence for changes in groundwater levels due to rainfall.

Materials and Methods

STUDY SITE

The Romwe Catchment is located in southern Zimbabwe, 86 km south of Masvingo (20° 45′ S, 30° 46′ E) (Bromley *et al.*, 1999). The 4.6 km^2 catchment includes areas of rainfed cultivation on the valley floor and miombo woodland on the surrounding hillslopes. Average annual rainfall over the period 1952–93 at a rainfall station located 12 km from the catchment was 585 mm. Rainfall is strongly seasonal with 84% received on average in the summer rainy season between November and March.

In this paper, groundwater levels are simulated for a location having well-structured sandy clay soils with a strong red colour, widely known in Zimbabwe as red clay soils. These soils are derived from pyroxene gneiss, rich in ferro-magnesian minerals such as pyroxene, mica and amphibole, and are prevalent in the northern part of the catchment where the most important and productive water wells are sited. A typical topsoil horizon within the plough layer (< 0.15 m) consists of 72% sand, 4% silt and 24% clay. Clay content tends to increase with depth, up to maximum recorded values of 46%. Little variation in bulk density was noted, with average values of 1.34 t m^{-3}.

Water balance measurements were made for a 2.4 ha surface water sub-catchment in the northern part of the area where the freely draining red clay soils overlie a weathered aquifer. This sub-catchment, subsequently referred to as the Red sub-catchment, comprises two fields with a cropped area of 1.7 ha. The remaining area is scrub and sparse woodland vegetation on the flanks of the fields. Further details of the sub-catchment location, characteristics, instrumentation and hydrology are given by Butterworth *et al.* (1999b). Groundwater level measurements presented in this paper were measured at a site about 200 m from the sub-catchment.

MODELS

Two different modelling approaches were used to simulate groundwater levels; the first is a physically-based lumped parameter soil water balance model (*ACRU*), and the second an empirical model (cumulative rainfall departure method).

The ACRU model

ACRU is a physical conceptual model for distributed catchment simulations on an irregular cell or sub-catchment basis, developed at the University of Natal, South Africa. In this study, the soil water balance component of *ACRU* Version 323 was used in lumped mode to calculate drainage. Groundwater levels were simulated separately due to limitations in the present groundwater module of the model for this particular study site. Currently *ACRU* can only simulate an aquifer which is permanently connected to surface water courses. In Romwe, and similar areas, the aquifer is disconnected from surface water courses for most of the year and discharges to streams for limited periods during wet years.

The *ACRU* model is flexible and can be configured to suit different conditions and the level of input data available (Schulze, 1995; Smithers and Schulze, 1995). *ACRU* is based around a two layer 'tank' or 'bucket' type soil water budgeting model. Infiltration into the soil profile depends upon net rainfall after interception losses and abstractions due to runoff. Canopy interception losses were determined using the Von Hoyningen-Huene method (1983), which relates interception loss to gross rainfall and the canopy's leaf area index (LAI). Stormflow is simulated according to net rainfall, antecedent moisture conditions, and surface roughness, using a modified version of the SCS stormflow equation (United States Department of Agriculture, 1985). Soil water storage for a two-horizon soil profile is determined using inputs for permanent wilting point, field capacity and porosity. 'Saturated' and unsaturated drainage are simulated from the A to B horizon, and from the B horizon into the intermediate store below the soil layers. 'Saturated' movement occurs when the soil water content of the layer is in excess of field capacity, and varies with soil texture. Slow unsaturated soil water movement is simulated both upwards and downwards when a soil water content gradient exists between the upper and lower horizons. Evaporation is simulated from the soil surface and from vegetation. Uptake of water and evaporation by plants occur from both soil layers according to atmospheric demand (i.e. potential evaporation), LAI, soil moisture content and the relative distribution of active roots between the two horizons. The amount of energy available for transpiration is determined from potential evaporation and modulated by LAI according to equations by Ritchie (1972). Actual transpiration equals the maximum potential transpiration when there is no soil moisture stress on plants, and the level at which moisture limits conditions for transpiration depends on the vegetative cover's critical leaf water potential and atmospheric demand. Soil water evaporation may occur only from the upper soil layer and is calculated for wet and dry stages following the analysis of Ritchie (1972).

On days when drainage out of the B-horizon was simulated from the soil water balance model, groundwater level rise was predicted using the equation

$$h_{t2} - h_{t1} = \frac{D}{S_y} \qquad (1)$$

where h_{t2}—h_{t1} is the groundwater rise between times t_1 (start of day) and t_2 (end of day) due to an amount of drainage D at a site with specific yield S_y expressed as a fraction (Price, 1996). Owing to the difficulty of obtaining reliable measurements of S_y for the Romwe aquifer (Macdonald *et al.*, 1995), this quantity was optimised over the period for which observed groundwater levels were available. Preliminary analysis showed that a poor correlation between simulated and observed groundwater levels was obtained using a depth-constant value for S_y. The degree of weathering decreases towards the base of a profile (Chilton and Foster, 1995) so that a linear function, used to describe S_y as a function of depth, accounted for the corresponding reduction in storage with depth. A minimum value was input for the base of the weathered aquifer and a maximum value for the top of the aquifer at the soil surface.

Groundwater discharge was predicted using a groundwater recession function parameterised from measurements of falling groundwater levels during periods when recharge was assumed to be zero, following the procedures described by Bredenkamp *et al.* (1995) based on the work of Ernst (1962), De Vries (1974) and Gieske (1992). An exponential equation of the form

$$h_{t2(NR)} = h_{t1}e^{yt} \qquad (2)$$

was used to describe the groundwater recession curve at a given site, where $h_{t2(NR)}$ is the groundwater level above the base of the aquifer at the end of a day given no recharge, and y is a response factor which describes the exponential decay in groundwater levels over time t. This response factor is inversely proportional to the specific yield of the aquifer and directly proportional to the transmissivity. Groundwater levels were therefore calculated on a daily basis as the sum of the initial groundwater level and calculated rise if drainage occurred on the given day, less the expected recession due to groundwater discharge. This may be expressed as

$$h_{t2} = h_{t1}e^{yt} + \left(\frac{D}{S_y}\right) \qquad (3)$$

The Cumulative Rainfall Departure (CRD) method

Bredenkamp *et al.* (1995) note that, in addition to frequent observations that cumulative rainfall departures (CRD) and groundwater levels are correlated, the relationship between the two series may be derived from first principles. For a specific aquifer, water levels will fluctuate according to the cumulative rainfall departure from the mean with a proportionality coefficient = a/S_y, where a is the fraction of rainfall that constitutes recharge and S_y is the specific yield. The CRD method is analogous to a simple bucket or tank type soil water balance model where the mean rainfall defines the size of a soil water store. For periods when the mean rainfall is exceeded, this store overflows, resulting in drainage and groundwater rise. When rainfall is below the mean value, groundwater levels fall by an amount related to the difference between rainfall and the mean.

Improved relationships between CRD and groundwater levels may be obtained using the most appropriate short and long-term 'memory' periods for the aquifer in question, rather than calculating the CRD from the long-term mean rainfall (Bredenkamp *et al.*, 1995). The short-term memory accounts for the time-lag in groundwater response to rainfall and can incorporate carry-over of recharge from year to year. The long-term memory represents the period over which the long-term reference rainfall is calculated. The equation used for calculating the CRD at a certain time interval i may therefore be expressed in the form;

$${}^{m}_{n}CRD_i = \left(\frac{1}{m}\sum_{j=i-(m-1)}^{i} Rf_j\right) - \left(k \times \frac{1}{n}\sum_{j=i-(n-1)}^{i} Rf_j\right) + (CRD_{i-1}) \qquad (4)$$

where m is the short-term memory period, n is the long-term memory period, Rf_j is rainfall at the j^{th} interval and k is a proportional factor which for natural conditions equals one.

Cumulative rainfall departures were calculated using monthly rainfall totals. Calculations were made using various short- and long-term memory periods and the most appropriate averaging periods determined from correlation analysis with observed levels.

OBSERVED GROUNDWATER LEVELS

Groundwater levels were measured over four rainy seasons from late 1992 at an un-cased 100 mm diameter observation borehole (borehole G). Details of construction methods are given by Bromley *et al.* (1999), and a site location map and groundwater level hydrograph are included in Butterworth *et al.* (1999a). The borehole was 10.5 m deep with a gradual progression from soil to weathered gneiss at about 1.5 m. Depth to bedrock in this area is about 12 m. However, the deepest water levels recorded at the borehole during this period, which included measurements after the 1991/92 drought, were only 8.89 m, suggesting that levels do not recess into the bedrock at this location. Levels were recorded weekly, with additional daily readings made after large rainstorms.

METEOROLOGICAL MEASUREMENTS

From February 1994, rainfall was measured at the study site using a tipping-bucket raingauge installed at ground-level with an anti-splash grid. Additional daily rainfall data were available at the same site from November 1993 to January 1994. Long-term daily rainfall records were obtained for a Meteorological Department rainfall station located 12 km north of the catchment at Chendebvu Dam. Continuous daily observations were available from 1953, with the exception of the period November 1978 to August 1981. During this period, rainfall data from Chivi, located about 50 km north-west of the catchment, were used with a correction factor to allow for the slightly lower rainfall at Chivi. All rainfall data were corrected to equivalent rainfall at ground level using relationships determined at the study site between gauge type, installation height and rainfall catch (Butterworth, 1997).

Measurements of net radiation flux, wet and dry bulb temperature and wind speed were made at the study site from February 1994 for calculation of potential evaporation using the Penman (1948) equation as a reference. Potential evaporation over the period 1953–94 was calculated from daily maximum and minimum temperatures at Masvingo, 86 km north of the catchment, using the Hargreaves and Samani (1985) equation with a correction factor determined from comparison of the Hargreaves and Samani (1985) and Penman (1948) equations over a 22 month period in 1994–95 (Butterworth, 1997).

MEASUREMENTS FOR PARAMETERISING THE SOIL WATER BALANCE MODEL

With the exception of leaf area index, all *ACRU* model parameters were determined from measured or published sources, without calibration against observations. In the 1994/95 cropping season, maize was cultivated by the farmer in both fields in rows approximately one metre apart. Over daily periods, radiation interception by the maize canopy was determined using tube solarimeters (Delta-T Devices Ltd., Cambridge) positioned above and below the canopy at five locations within the Red sub-catchment. Leaf area index was determined from the fractional radiation intercepted by the canopy using a modified light extinction coefficient of 0.25, because plant uptake for the sparse crop in widely-spaced rows was overestimated when simulated using published coefficients in the range 0.4–0.7 (Monteith, 1969). The same vegetation parameters were used for each year of the simulation because maize is the most frequent crop. No attempt was made to vary the vegetation cover to account for differences in the seasonal development of the canopy due to differences in rainfall distribution between years. The effective rooting depth was assumed to be 1.3 m and the root distribution information was from parameters suggested by Smithers and Schulze (1995).

Soil water content at soil water potentials nominally representing permanent wilting point (–1.5 MPa), field capacity (–0.01 MPa) and porosity were calculated from a laboratory-derived soil moisture characteristic curve (Butterworth, 1997). Soil water redistribution factors according to textural properties and streamflow parameters were taken from values given by Smithers and Schulze (1995).

OBSERVATIONS FOR TESTING SOIL WATER BALANCE MODEL

The soil water balance model was tested against measurements of surface runoff, soil water content, drainage and soil water evaporation during the 1994/95 season, and surface runoff during the 1995/96 season. Runoff from the sub-catchment was gauged at a V-notch weir (Bureau of Reclamation, 1984). *In-situ* soil water measurements were made with a neutron probe (Didcot Instruments, UK) at approximately weekly intervals. A grid of 24 aluminium access tubes for neutron probe measurements was installed, although continuous records were obtained from only 17 sites. The probe was calibrated using parameters determined from soil samples analysed by CEA (Cadarache, France) using the neutron-capture technique developed by Couchat *et al.* (1975). Estimates of drainage at these sites were available from analysis of soil water content changes and soil water potential profiles measured using tensiometers, using the *zero flux plane* (ZFP) method (Butterworth, 1997). Soil water evaporation was measured using microlysimeters in January 1995 over three drying periods between rainstorms. Detailed testing of the *ACRU* model output against field measurements is reported in Butterworth (1997).

REPRESENTING THE EFFECTS OF SURFACE REDISTRIBUTION OF RAINFALL ON OUTPUT FROM THE SOIL WATER BALANCE MODEL

Surface redistribution of rainfall has been shown to be an important factor affecting drainage from the soil profile, particularly in relatively dry years (Butterworth *et al.*, 1999b). To incorporate this process in the model simulations, *ACRU* runs were repeated using 70, 80, 90, 110, 120 and 130% of the infiltration to the profile using normal rainfall input and runoff simulation parameters. This is easily simulated using the options provided in *ACRU* to disable runoff and to apply correction factors to rainfall input.

Results and discussion

COMPARISON BETWEEN OBSERVED AND SIMULATED GROUNDWATER LEVELS

Observed groundwater levels over the period 1992–96 and simulated levels using *ACRU* and CRD methods are shown in Fig. 1.

ACRU Method

Groundwater levels simulated using *ACRU* follow the observed levels closely over the four years of comparison. Both the timing and magnitude of the groundwater level rise are accurately represented and the pattern of recession is well described (Fig. 1a). The optimised values of specific yield used in the groundwater level simulation were 1.6×10^{-5} at 8 m depth (at the base of the aquifer) and 6.0×10^{-4} at the ground surface, with a linear interpolation between these depths. These figures compare with a measured specific yield of 1.6×10^{-5} determined at a nearby hand-dug well from a short pumping test (Macdonald *et al.*, 1995).

There are two notable differences between observed and simulated levels. Towards the end of December 1992, simulated groundwater levels rise considerably before the observed main rise in levels in mid-February 1993, although a relatively small rise in observed levels does occur at the same time as the simulated rise. The most likely explanation is that up to November 1993 rainfall data were taken from Chendebvu Dam located 12 km away, rather than in the catchment itself. Considerable spatial variation in rainfall over distances of a few kilometres is common due to the convectional nature of rainfall. As the actual rise in the catchment was small, it is likely that the rainfall was less than at Chendebvu Dam.

The second major difference between observed and simulated water levels occurs in the 1994/95 rainy season. In February 1995, a rise in groundwater levels of 0.94 m is simulated compared to an observed rise of 2.40 m. One possible explanation for the underestimation of groundwater rise in the 1994/95 season is underestimation of drainage from the unsaturated zone. Simulated drainage for this season amounted to 7 mm compared to an average of 24 mm determined from soil moisture measurements using the ZFP method. When surface redistribution is represented in the model, considerably more drainage from the soil profile is simulated in low recharge years. Simulated drainage with infiltration inputs to the profile between 70–130% of lumped infiltration amounted to 52 mm for the 1994/95 season. This results in a slight overestimation in groundwater rise in this year, rather than underestimation when surface redistribution of rainfall is not represented (Fig. 1b).

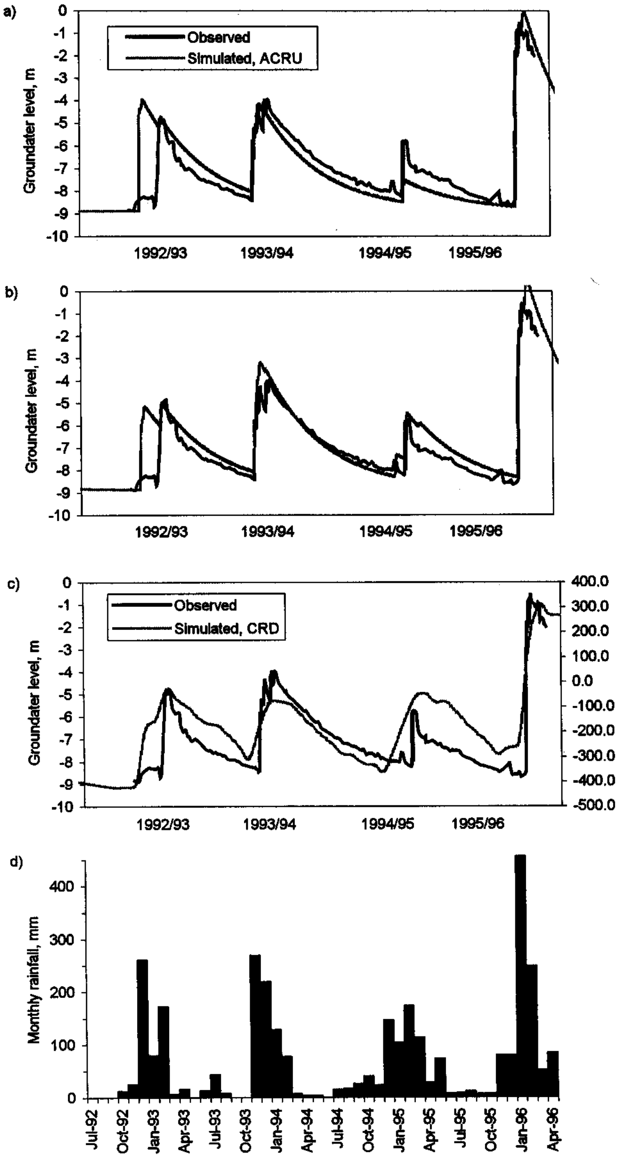


Fig. 1. *Observed and simulated groundwater levels, 1992-96, a) ACRU, b) ACRU with surface redistribution of rainfall, c) CRD 1:12, d) monthly total rainfall.*

CRD method

The best correlation between observed groundwater levels and CRD was obtained using short and long-term memory periods of 1 and 12 months respectively, with a correlation coefficient of 0.90. Levels are simulated with less sensitivity than using *ACRU* due to the monthly calculation on which the CRD was based. However, the annual fluctuations in levels track the observed fluctuations relatively well (Fig. 1c). Groundwater rise was also overestimated in the 1994/95 rainy season using this method, due to the well-spaced distribution of rainstorms in this year.

The two approaches have different advantages and disadvantages for the simulation of groundwater levels in the shallow aquifer. The empirical CRD method is a simple and rapid method of predicting groundwater level fluctuations from rainfall, requiring none of the parameters needed by the physically based model, although observed groundwater levels are required for each site over a reasonable period. Given this simplicity, and the ability to include representation of abstraction, this method has potential for routine use in the management of abstraction from water points. The physically-based approach has greater data requirements for parameterisation and testing of the model, but ultimately has greater capabilities, for example, to simulate the effects of changes in land use and management on groundwater levels.

SIMULATED GROUNDWATER LEVELS, 1952–96

Simulated monthly groundwater levels over the period 1952–96 using *ACRU* and CRD methods are shown in Fig. 2. Simulated levels reflect the large annual fluctuations typical of the shallow weathered aquifer due to relatively rapid groundwater recharge and recession (Butterworth *et al.*, 1999a).

The average annual rise in groundwater levels, defined as the difference between minimum levels prior to recharge reaching the aquifer and the maximum level observed during any given wet season, was 3.03 m using the *ACRU* model. However, there is a great deal of temporal variability and for 17 of the 43 seasons zero or negligible recharge is simulated, while the highest rise was 8.62 m. The mean simulated recharge from the soil water balance model was 100 mm (range 0–417 mm), and this increased to 135 mm (range 0–540 mm) when surface redistribution of rainfall was incorporated. This is about four to five times greater than the estimate of 24 mm for recharge on this soil type using the chloride balance method (Macdonald *et al.*, 1995). The large variation in rainfall between years is responsible for the temporal variation in recharge and simulated groundwater levels. Little or no recharge is generally simulated in low rainfall years when groundwater drought conditions are likely to develop in the weathered aquifer. Comparison between annual total rainfall and simulated recharge suggests that on average, total annual rainfall above a threshold of 507 mm or 466 mm (including surface redistribution of rainfall) will result in recharge, although the distribution of rainstorms in a year is also important (Butterworth *et al.*, 1999a). This estimate of annual rainfall required for recharge to occur is greater than the tentative value of 400 mm suggested for the region by Houston (1988), although, importantly, it is based on ground-level rainfall and relatively low permeability soils which both result in calculation of a higher threshold.

Particularly noticeable is the distribution of years when zero or negligible recharge occurs (Figs. 2a and b), although few zero recharge years are simulated using the CRD method (Fig. 2c). As was observed in 1994/95, the CRD approach is less accurate in low recharge years, since it fails to represent adequately the effects of seasonal distribution in rainfall. Considering the *ACRU* simulation, years of predicted groundwater drought recur throughout the period since 1953. Two periods of longer consecutive drought are noticeable, when seasons with zero recharge are clustered together. In the period between 1953/54 and 1966/67, groundwater drought is simulated for 7 out of

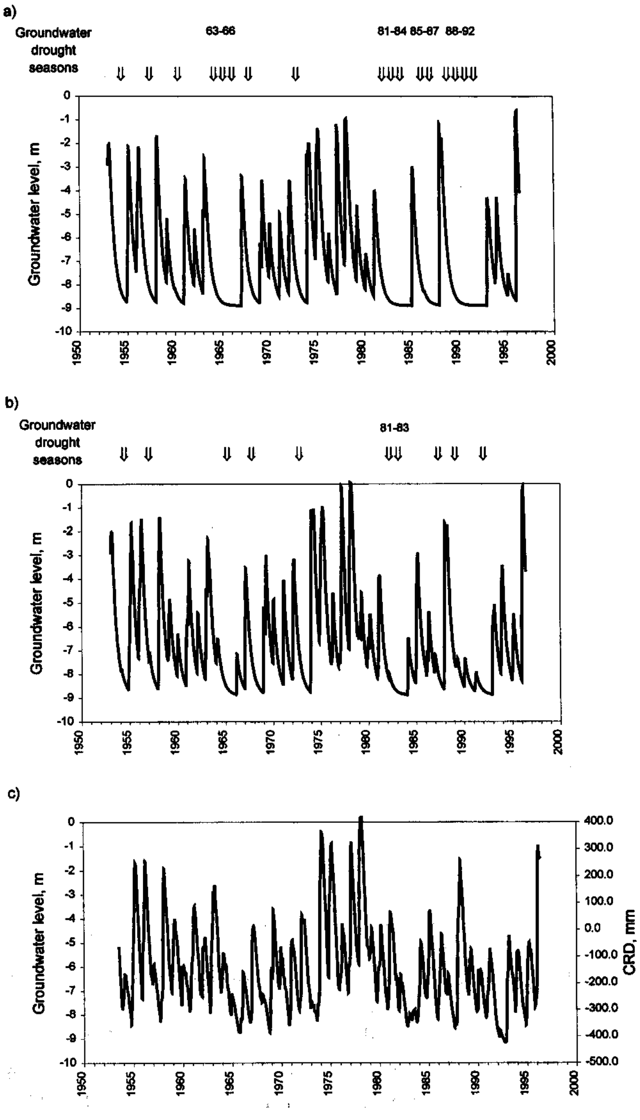


Fig. 2. *Simulated groundwater levels, 1953-96, a) ACRU, b) ACRU including surface redistribution of rainfall, c) CRD 1:12.*

the 15 seasons, with 3 consecutive years of no recharge in the 1963/64, 1964/65 and 1965/66 seasons. More extreme is the period 1981/82 to 1991/92 when no recharge is simulated for 9 out of the 11 seasons. This clustering of consecutive seasons of groundwater drought is unprecedented in the period since 1953. The simulation of groundwater drought seasons is slightly less severe when the effects of surface redistribution of rainfall on drainage are represented (Fig. 2b), in which case only 10 out of 43 seasons show no recharge for this simulation.

LONG-TERM TRENDS IN GROUNDWATER LEVELS

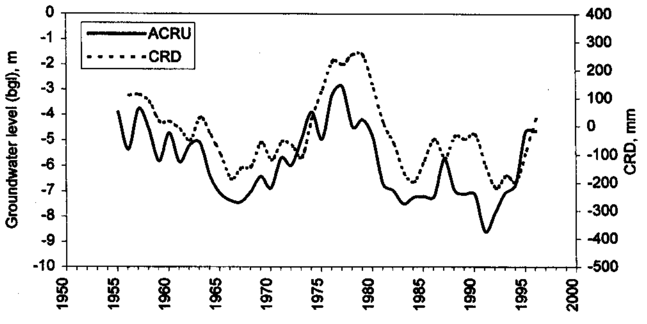
Long-term trends in simulated end of wet and dry season groundwater levels are shown in Fig. 3 for the two modelling methods. The ends of wet and dry seasons water levels were taken nominally as the end of March and the end of September, and levels were smoothed using a three year average to reduce the degree of annual fluctuation. Simulated groundwater levels show considerable long-term variation since the 1950s, generally reflecting cycles of above and below average rainfall. Averaged levels using both the *ACRU* and CRD methods follow very similar trends. There was almost no difference in averaged levels using the *ACRU* model with or without accounting for the effects of surface redistribution of rainfall. Simulated water levels fall during the 1960s and early 1970s during a period of generally low rainfall. Water levels rise during the late 1970s due to a series of high rainfall years, before falling again in the early 1980s, stabilising only slightly in the second half of the 1980s, before falling to the lowest levels in the early 1990s prior to a significant rise due to the very wet 1995/96 season.

The largest simulated fluctuations over recent decades are in the water levels at the end of the wet season. Taking the *ACRU* simulated levels, end of wet season levels are shown to vary between about 3 m below ground level in the late 1970s and about 8.5 m in the early 1990s. This decrease in average levels would be expected to have had huge effects on the observed hydrology of the catchment, in particular the duration of spring and stream flows.

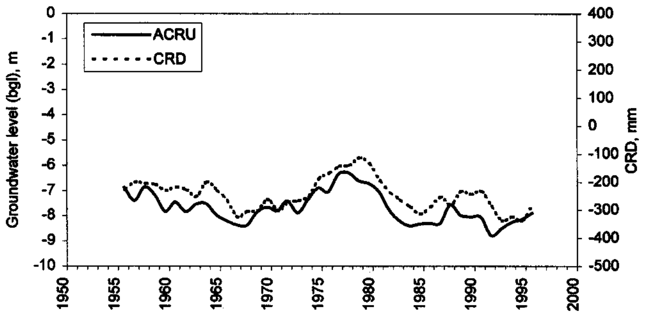
Water levels at the end of dry season fluctuate less than those at the end of the wet season, with a range between about 6 m below ground level in the late 1970s and 9 m in the early 1990s. A fall of almost 3 m in end of dry season regional water levels during the 1980s and early 1990s to prolonged low groundwater levels would be expected to have had a substantial impact on well performance. This evidence supports the communities' observations of generally falling water levels during this period which resulted in considerable efforts to deepen and dig additional wells. Between 1980 and 1992 the number of wells in and around the catchment increased from 9 to 35 and many existing wells were deepened. However, given the low abstraction from even this increased number of wells (about 1 mm over the catchment area) and the relatively small changes in land use and management over this period, the simulations show that rainfall variations were likely to have been a far more important cause of falling regional groundwater levels than human impact.

During the late 1980s and early 1990s, drought relief projects supported construction of large numbers of boreholes and wells throughout the region. One fortunate aspect of the expedited groundwater resource development during this period of generally low groundwater levels, is that the successfully commissioned water points are more likely to be sustainable through future periods of prolonged low rainfall. However it is possible that current groundwater development schemes, constructed during a period of generally high groundwater levels, will be less sustainable. The modelling techniques presented can be

a) End of wet season groundwater levels



d) End of dry season groundwater levels



c) Annual rainfall

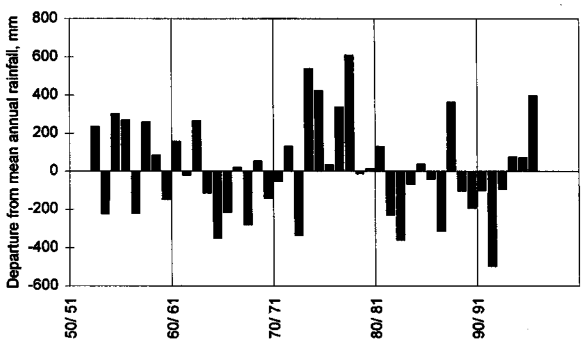


Fig. 3. *Simulated trends in groundwater levels, 1953-96, a) end of wet season, b) end of dry seasons c) annual rainfall departures from mean.*

used to develop design criteria appropriate for sustainable long-term groundwater development in a region with widely fluctuating rainfall patterns.

Conclusions

1) Groundwater levels in the shallow aquifer were simulated successfully using two different modelling approaches, a soil water balance model (*ACRU*) and the cumulative rainfall departure method. The long-term trends simulated by both methods correspond very closely. The techniques have different strengths in studies of groundwater resources from shallow aquifers.

2) Groundwater levels can be simulated most accurately using the drainage obtained from a soil water balance model (*ACRU*) and a model relating drainage to groundwater level rise, on the assumption that groundwater levels recess exponentially. The soil water balance model requires considerable data inputs to parameterise and run the model, and observed groundwater levels are necessary to determine the aquifer storativity. However, the model can be used for a wide range of applications including evaluation of the effects of climatic fluctuations and of land use and management changes on groundwater levels.

3) Over short time periods, groundwater levels are simulated with less sensitivity using the CRD method, although this provides a simple and rapid technique for predicting levels from rainfall data. This method is better suited to routine use in the management of abstraction from water points and in studies where fewer data are available.

4) Simulated groundwater level fluctuations since the early 1950s show that large annual fluctuations are characteristic of the shallow aquifer and that, superimposed on these large yearly variations, long-term trends in levels reflect cycles of sustained above and below average rainfall. The main cause of severe groundwater stress in the area in the early 1990s is the long period of relatively low rainfall from 1981 resulting in average end of dry season levels falling by almost 3 m between the late 1970s and early 1990s, rather than human impact.

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