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DEVELOPMENT OF A GROUNDWATER MODEL OF THE ROMWE MICRO-CATCHMENT, ZIMBABWE

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DFID
INTERMEDIATE TECHNOLOGY
CARE
Institute of Hydrology
R&SS

General Project Outline

The Zimbabwe: Micro-Catchment Management and Common Property Resources Project (1999-2001) is a research programme implemented by a consortium of institutions, including the Institute of Environmental Studies (IES) (University of Zimbabwe), the Institute of Hydrology (IH) (UK), the Department of Research and Specialist Services of the Ministry of Lands and Agriculture (Zimbabwe), Intermediate Technology Development Group (ITDG), CARE International in Zimbabwe and the Center for International Forestry Research (CIFOR). The project is funded by the UK Department for International Development (DFID), under its Renewable Natural Resources Knowledge Strategy (RNRKS). The funding is provided through the Semi-Arid Production Systems (SAPS), a portfolio under the Natural Resources Systems Programme (NRSP) which in turn is one of the eleven programmes comprising RNRKS. SAPS is managed by Natural Resources International Limited (NRIL). A component of the research is funded through CIFOR on the project entitled "Stakeholders and Biodiversity in the Forests of the Future" which is funded by the Swiss Development Cooperation.

The objective of the project is to develop and promote appropriate strategies for integrated management of micro-catchments in semi-arid areas in order to improve livelihoods and alleviate poverty through more efficient and innovative use of water resources. The focus is on common property resources (CPRs) although other resources within the catchment are also included in the work. The key project components are: strengthening the capacity of emerging and existing institutions to manage CPRs; characterisation of key biophysical linkages among micro-catchment components and such information made accessible to CPR management; and testing and development of technical and other options for improved micro-catchment management. The emphasis is on the water resources. A guiding hypothesis is that water in semi-arid regions is so valuable that it can be used as the entry point for the management of a broad range of CPRs.

The project is conducted in Chivi District of Masvingo Province in southern Zimbabwe. The area lies in a semi-arid region of the country, marked by unreliable rainfall, frequent droughts, recurrent crop failures and recurrent livestock mortality. CPRs are widespread and significant in the household livelihood systems.

The direct beneficiaries are the smallholder farmers, particularly women who bear the burden of rural livelihood constraints. Government and non-governmental agencies responsible for key natural resources, and planners at national, district and local levels are also the target institutions. The project is relevant to communally-managed dryland areas world-wide.

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Acknowledgements

This paper is a slightly modified version of the third chapter of the authors PhD thesis. The thesis is a cross-disciplinary investigation of water resources management in the Romwe catchment in south-eastern Zimbabwe. Research work at the Romwe catchment has been funded since 1991 by the UK department for international development (DFID) under a number of different projects, primarily, the UK Institute of Hydrology's 'Romwe catchment study' (project no. R5846), which ended in 1998, and the ongoing 'Zimbabwe: micro-catchment management and common property resources' (project No. R7304) under the lead of the University of Zimbabwe's Institute of Environmental Studies (IES). For a background to the research work at the Romwe catchment see Lovell et al. (1998) and Frost and Mandondo (1999).

Development of a groundwater model of the Romwe Micro-catchment, Zimbabwe

Patrick Barré Moriarty[1]

Abstract

This paper describes the development and use of a groundwater model of the Romwe micro-catchment in southern Zimbabwe. The model supports our conceptual picture of how the groundwater system works in the freely draining soils of the 'red soil' areas of the catchment. The model shows that groundwater recharge is indeed high, but largely lost to recession due to abstraction by deep rooted vegetation. This is an important finding as it has profound implications for the management of groundwater resources. The importance of 'sump points' is illustrated by the model. These are lower down in the catchment, where groundwater collects and pools. One contains the present collector well in addition to some of the most productive private wells. In all of the simulations, groundwater abstraction by humans was insignificant when compared to that by vegetation/evaporation. The concept of well failure due to low transmissivity rather than to lack of water, and despite an otherwise high 'regional' water table, is important in understanding the mechanisms of crystalline basement aquifer behaviour. The model gave strong support to the development of further productive water points in the catchment. Given that the current collector well is designed to irrigate half a hectare it is suggested that up to a further 5 ha could be irrigated in the zones of groundwater accumulation using either collector wells or large diameter wells. The model suggests that the 'Romwe aquifer' is largely isolated from the larger catchment downstream. At a river-basin scale it suggests that the contribution of groundwater recharge to river base flows will be negligible for all but those micro-catchments closest to the rivers. It also suggests that, apart from at the micro-catchment scale, there will be negligible effects from change in land use on groundwater resources further downstream. Even within the micro-catchment there is no guarantee that managing one section will have an effect on the groundwater of another. Each catchment needs to be examined and treated for its own unique range of soils, geology and topography. Given the effort in time and resources put into developing the groundwater model of the Romwe aquifer, it is difficult to see how the approach of using a distributed groundwater model would be of much use in terms of general 'scaling-up'.

The complexity of the basement means that entirely local effects control a highly localised aquifer. To talk about groundwater as a shared resource at a river-basin scale in such a framework is meaningless. It is a wholly local resource, common only to those people living in the immediate area, or micro-catchment. In a way, this lends it to a highly localised common property resource management approach – decisions on runoff control measures, forestry or irrigation will have a wholly local effect and as such should be easily understood and made relevant to local communities' livelihoods.

Introduction

The Romwe catchment is a small (4.5km^2) headwater catchment of the Runde river, located about 80km south of Masvingo, provincial capital of Masvingo Province. The catchment community of approximately 250 people are mainly engaged in dryland agriculture, although with a rapidly increasing number also undertaking small scale irrigation using groundwater (Moriarty and Lovell, 1997). The catchment has an extensive network of instruments monitoring physical hydrology (Butterworth, 1997), and the community of the catchment and surrounding area have taken part in the surveying to investigate the role of groundwater in their livelihoods.

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This paper describes the development and use of a groundwater model of the catchment, developed using the USGS Modflow package (McDonald & Harbaugh, 1988). The model was developed for a number of reasons. The first of these was, to investigate and test the conceptual validity of high recharge and discharge values estimated for the shallow regolith aquifer. Table 1 below shows the average values for recharge and discharge from the catchment calculated using the water balance method. This was a refined version of a method previously used in the Romwe catchment (Lovell et al. 1998), which by taking account of the change in soil moisture storage substantially reduced the calculated recharge. It also resulted in a reduced average value for catchment specific yield, from approximately 7% to 3.5%.

Table 1 Average catchment recharge and discharge between 1993 and 1998

1993/94		1994/95		1995/96		1996/97		1997/98	
recharge	discharge	recharge	discharge	recharge	discharge	recharge	discharge	recharge	discharge
86	74	24	43	188	136	147	126	133	112

It was clear that the low human abstraction of 1-2 mm/year could not be causing such high recession, and the second use of the model was to test the hypothesis that it was mainly due to water use by vegetation, particularly deep rooted vegetation lying along the valley floor of the catchment. The other potential cause of recession was drainage from the regolith aquifer to deeper fractures in the underlying bedrock, and from here out of the micro-catchment.

Finally, the model was developed to allow estimates to be made of the likely limits to sustainable groundwater abstraction by the catchment community, and to underline the effects of spatial heterogeneity within the aquifer on water resource occurrence and pooling.

The Modflow package was selected as it is widely used and accepted within the hydrogeological community (Osiensky & Williams, 1997; Anderson & Woessner, 1992), and is relatively easy to use and parameterise.

Conceptual framework for modelling

Before describing the modelling process it is important to outline the philosophical framework within which it was carried out. Models may be used for two broad (and overlapping) types of work: the first is to 'represent' a system and make specific predictions about its behaviour under different conditions. While this is probably the most common perception of models use, it was not applied in this case. The second use of models is as an experimental or teaching tool – with this approach a model is used to investigate, within an objective and structured framework, how a conceptualisation of a system may work in practice, or to demonstrate the effects on a system of altering one of its component parts. The distinction is fine, but nonetheless important. A good example of the second approach is given by Carter et al. (1994) who used a groundwater model to test a conceptual model of a shallow aquifer system in dunefields in northern Nigeria. The sparse available data meant that the model results could not have withstood scrutiny for decision making, however, they did show that the conceptual structure developed was indeed one satisfactory explanation of observed groundwater behaviour, and served to help direct future research to further clarify the issues highlighted by the conceptual model.

A key difference between the approaches is that while modelling for prediction will typically demand a high degree of replicability of observed data over a long time period, a model used to test system understanding can make use of considerably less observed data and employ greater latitude in mimicking observed behaviour. The essence of the approach is to concentrate on replicating broad behavioural types and trends rather than becoming obsessive about the detail. This is particularly true when trying to model a system as complex as that of the Romwe catchment, where geological and soil micro-structures may have large effects on water table behaviour over a relatively short distance. The model has to be either unrealistically (or impracticably) detailed – or must accept that a 'Romwe like' system is being modelled rather than Romwe itself.

All models represent some form of abstraction over reality – the essential question is at what point the generalisations and abstractions become so generalised as to render the outputs of the model meaningless. The golden rules of modelling are to be absolutely clear at the outset of the exercise as to the issues the model is to resolve; and to clearly identify the limits within which it may be expected to replicate system behaviour.

Model development

Modelling is an iterative activity; an initial model is developed and run, output is analysed and then the model is redesigned in the light of the output and its relationship to expected values. In addition, as modelling gives insight into system behaviour it may become necessary to re-evaluate other data about the system so as to allow the model to be reformulated (Anderson & Woessner, 1992). Thus the analysis of the recharge data reported at the start of this paper and the modelling reported in this paper are separated only for stylistic reasons, and only represent the order in which activities took place inasmuch as initial analysis of groundwater did come before initial model development.

Modelling was generally carried out within the framework of Waterloo Hydrogeologic's Visual Modflow software, which offers useful pre- and post-processing for the Modflow programme. In addition some analysis and delimitation of modelling zones was carried out within the GIS developed to store spatial data about the catchment (Moriarty et al. 1999). Prior to undertaking the modelling work I attended a one-week training course in Visual Modflow at the University of Newcastle. Where un-referenced assertions about basic model design and behaviour are made, it may be assumed that this reflects course material. Two other main sources were Anderson and Woessner's (1992) text book on groundwater modelling, and the internet based 'Modflow Help File' (Diodato, 1998)

USGS Modflow groundwater model

The USGS Modflow is a modular, fully distributed, quasi-three-dimensional groundwater model in which Darcy's law and the continuity equation are solved numerically using a finite difference technique. The model is quasi-three-dimensional in that it allows vertical flow to occur between layers in the model, which is developed within a grid of rectangular cells.

Darcy's law states that in terms of flow rate Q through a cross sectional area A:

$$Q = KAi = KA\frac{dh}{dx}$$

where i is the hydraulic gradient

$\frac{dh}{dx}$ the specific discharge

K the hydraulic conductivity

The USGS Modflow equation is based on a numerical solution of the three dimensional Darcy equation and the continuity principal which may be stated as:

Inflow = Outflow – Change in storage, or

$$q_x = \left(q_x + \frac{\partial q}{\partial x} x \right) + S_s xyz \frac{\partial h}{\partial t}$$

where

- S_s is the specific storage

- $\frac{\partial h}{\partial t}$ is the change in head with time (specific yield)

Applying Darcy's law and removing the flow equations gives:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-W=S_s\frac{\partial h}{\partial t}$$

where

- K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y and z coordinate axes which are assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1})
- h is the potentiometric head (L)
- W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1})
- t is time

The equation describes groundwater flow under non-equilibrium conditions in a heterogeneous and anistotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

Model development

Developing a groundwater model within Modflow, particularly in the complex terrain of the Romwe catchment, is not simple. The process was highly iterative as initial model configurations were discarded in the face of problems encountered. The process of development will only be briefly described. It was time consuming and, even after several months effort, far from satisfactory. One of the effects of the changes necessary to make the model functional was a considerable simplification of the complex terrain of the catchment – another was the *de facto* abandonment of efforts to model the part of the catchment consisting of duplex soils with shallow sandy topsoil underlain by clay lenses. This latter was particularly disappointing, however, unavoidable due to the constraints of model development. Possible future approaches to modelling the grey duplex soils are discussed later in this paper.

Modflow is a quasi three-dimensional model – that is it permits layers of cells to be placed on top of each other to model different aquifer layers, aquitards, etc. Several different configurations were attempted for the Romwe aquifer model. However, the version that was finally used was a two layer model with one layer being dedicated to the regolith aquifer and one to the fractured basement aquifer. As will be mentioned in the next section the second layer was finally made inactive, meaning that the final model was essentially two-dimensional. A particular problem with modelling the basement aquifer of the Romwe catchment is the relatively thin layer of water-bearing strata being modelled, and the generally steep gradients encountered.

Conceptually the Romwe aquifer can be seen as a layer of icing lying over a lumpy cake, with the topography of the cake determining the location of the icing (water) far more than general head considerations. Nonetheless, the potential importance of regional pooling of groundwater from the point of view of water resource development makes it necessary to try to develop some idea of how quickly water will travel from the point where it initially infiltrates the soils to sump, and how much will be lost in transmission.

An advantage of the Visual Modflow package is that it can import elevations for cell layers from a number of external sources which meant that it was possible to develop a digital elevation model (DEM) of the aquifer surface in the GIS and to then import this into the model. The DEM was created in ArcView using digitised contours from 1:25,000 orthophoto maps. While this creates an acceptable surface for visual presentation, the interpolation method used meant that it tended to have sharp drops at contours and large flat areas between them which caused problems with modelling. The DEM was modified using data from spot elevations of piezometers and other instrumentation taken when the catchment was first instrumented, in addition to which the model was further smoothed on a cell by cell basis within Visual Modflow.

The bottom of the regolith was modelled by first creating a digital model of depth to hard rock using data from piezometer drilling logs, and then subtracting this from the DEM of the ground surface. Finally the depth of the second layer corresponding to the fractured basement was taken to be a uniform 20m below the bottom of the regolith.

Modflow is a grid based model, and the grid may be made as large or small as necessary. It is generally recommended to use a coarse grid where there are areas of minor interest or where change is likely to be gradual, and a finer one where there is more interest in water table behaviour or around points where the water table is expected to vary sharply (abstraction boreholes for instance). However, there are problems with the numerical solutions if the grid size varies too abruptly, and Visual Modflow provides a number of smoothing options to ensure this is avoided.

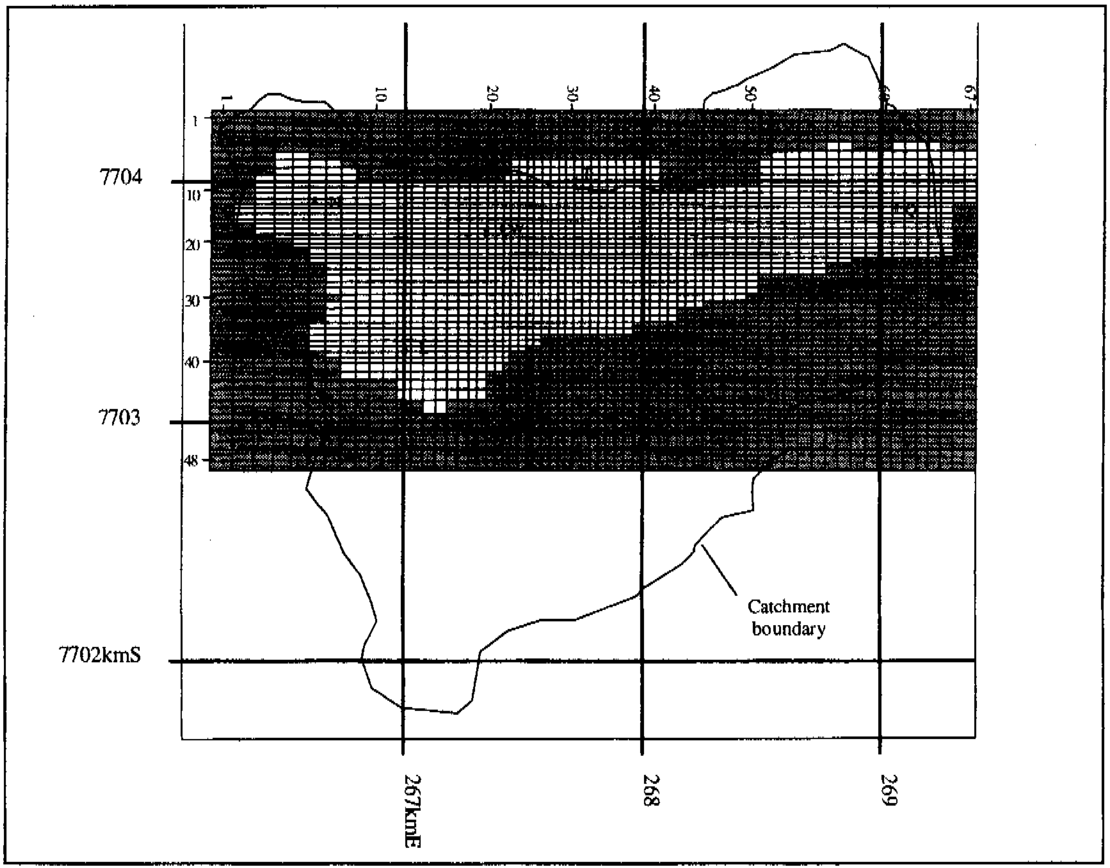

Figure 1 Model grid showing active and inactive (shaded) cells and the position of observation wells (CW = collector well; N = one of the observation wells)

The model grid finally adopted after much trial and error is shown in Figure 1. It consists of a grid of 48 rows and 67 columns with individual cell dimensions varying from 25m x 25m to 90m x 90m. In the figure the model grid is shown overlain onto the catchment grid and catchment outline. The numbers to the immediate left and top of the model grid refer to model rows and columns respectively; these are used to identify transects through the model in later illustrations. The shaded areas represent inactive cells at the edge of the aquifer. The two areas at the north and east of the catchment where active cells meet the edge of the model domain represent the approximate position of the groundwater divide (and hence a no-flow boundary).

Another major constraint and one that was to prove problematic with the development of this model is that vertical overlap between cells should not be less than one-third of their combined surface areas; this is because the flow from one cell to another in a layer is determined by the joint area between the two cells, and hence an unrealistically narrow common surface will impede or prevent flow from cell to cell. This was a particular problem in the steeply sloping gradients and thin regolith found in the Romwe catchment (see model cross sections, e.g. Figure 9) and meant that the model had to be adjusted considerably both by narrowing the grid and by excluding some potential aquifer areas. It was problems of cell overlap in the very thin layers needed to model the two to three layers found in grey duplex soils that forced the abandonment of this aspect of the modelling.

Model development and testing were carried out in three stages (with much iteration between them).

1. Initially an effort was made to develop a steady state model of observed water table topography at the end of the 1996 dry season. This was only moderately successful probably due to the very dynamic nature of the groundwater system. However, it did provide a base from which future modelling runs could be carried out (Visual Modflow allows the use of head files from previous model runs to be used as initial conditions for new runs), and also allowed a range of probable values for the main parameters to be identified.
2. The next stage consisted of carrying out dynamic modelling over initially one and then several seasons. It was at this point that serious problem with the Modflow programme became evident, namely that the model does not allow recharge to cells that have become dry (this is discussed further in the next section). The method used to get around this was only partially successful, and consisted of taking an end-of-dry-season level, and then adding recharge to this outside Modflow using the GIS. The main drawback to this method is that it does not allow for gradual recharge over a series of events to be modelled practicably, and instead recharge must be made as a single plug. In essence therefore dynamic modelling was restricted to aquifer discharge.
3. In the final stage of modelling, groundwater recession was examined over an extended period of 380 days (simulating the effects of a failed rainy season) for a number of different scenarios of both naturally occuring and man-made abstraction.

Use of a GIS as an overlay/pre-processor to the model

Code was written to allow the catchment GIS to read and write Visual Modflow grid, elevation and head files. Initially this was most important in developing the surface elevations of the model layers – which were derived from the catchment DEM. However, when later in the modelling process it became evident that there was no way around the failure of Modflow to allow re-wetting (see Section 5.4) by recharge to cells that have gone dry, extra code was written to allow the direct injection of user defined recharge into the model initial heads file. A recharge value was entered in the GIS which was then turned into an equivalent rise in groundwater level by multiplying it with the current value for S_y. This was then added to either the bottom of the cell, or the existing water level, with a check made to ensure that it does not then overtop the cell.

This was a cumbersome procedure, and far from ideal. As will be discussed later in this paper, for Modflow to be of more use in modelling shallow crystalline basement aquifers, the constraint of not allowing recharge to dry cells will need to be overcome. The GIS was also useful in delimiting areas of deep rooted vegetation, aquifer boundaries and other items necessary to the modelling process. Initially it was also used to delimit the extent of the 'clay' at the time when the duplex soils of the south-western catchment were being modelled separately.

Important simplifications and omissions

Several important omissions or simplifications needed to be made to make the model function and are listed and discussed below:

No re-wetting of cells

The most important simplification was that forced by the failure of Modflow to allow recharge to 'dry' cells. As in any given run a large number of cells become dry as the modelled water table recedes, they are then effectively 'turned off' with no way of introducing new recharge. This, as mentioned previously, meant that the annual recharge had to be modelled as a single 'plug' which was highly unsatisfactory.

In addition to this, while theoretically rewetting from neighbouring cells during a model run is allowed, in practice it creates problems and was not done. With the original Modflow it was impossible to re-wet a cell once it had become dry during a model run. Since then, however, a new mathematical solver was developed (the PCG2 solver - McDonald & Harbaugh, 1996) which allows for some re-wetting to occur. However, it is well known that getting the numerical model to converge with re-wetting activated is frequently difficult and that there is a tendency to instability in the results. This was found to be the case with the Romwe model, which always had stability problems due to the difficult geology being modelled. As a result it was impossible to use the re-wetting facility, without the model failing to converge to a solution. In general, by using the PCG package with a sufficiently small damping factor, this does not cause too much of a problem as cells only go dry when they should, rather than as a result of over speedy convergence to a solution (Osiensky and Williams, 1997). As a result a damping factor of 0.3 was used for most runs, thus minimising (though not eliminating) the number of incorrectly produced dry cells.

Entire catchment modelled as a single soil type

This, along with the use of an indirect method to introduce recharge, was the single most important difference between the model and 'reality'. In effect the aquifer being modelled is no longer the Romwe catchment, but a Romwe-like catchment, with Romwe depths of weathering but only partly representative of Romwe soils. The decision to abandon attempts to model the grey duplex soils was entirely practical. In part it was related to the already discussed problem of ensuring a minimum of one-third overlap between neighbouring cells in the same layer. Difficult in a single layer model, this would become almost impossible in a two or three layer model of the kind which would be necessary to deal with the sand, clay, and saprolite layers of the duplex soils. The second problem was related to the sharp boundary between a relatively conductive zone with high specific yield abutting onto a zone of sharply reduced yield and conductivity, and to the failure of the numeric engines to arrive at a solution in these conditions.

Relief and layer thickness

As mentioned earlier, for the model to behave properly there should be a minimum of one third vertical overlap between neighbouring cells in the same layer. This makes it very difficult to model steep slopes or abrupt changes in aquifer depth. As a result the model is a 'smoothed' version of the Romwe aquifer, and slightly reduced in extent as some steeply sloping edge areas had to be excluded. However, in essence the model remains true to what is known about Romwe, in particular in having the zones of deep weathering associated with the most productive groundwater areas on the red side. Figure 2 shows how depth varies along a longitudinal slice through the north side of the model aquifer. The figure also shows the groundwater table some way into the dry season, with the tendency of the system to dry out in areas of shallow weathering and collect in deeper ones is clearly visible.

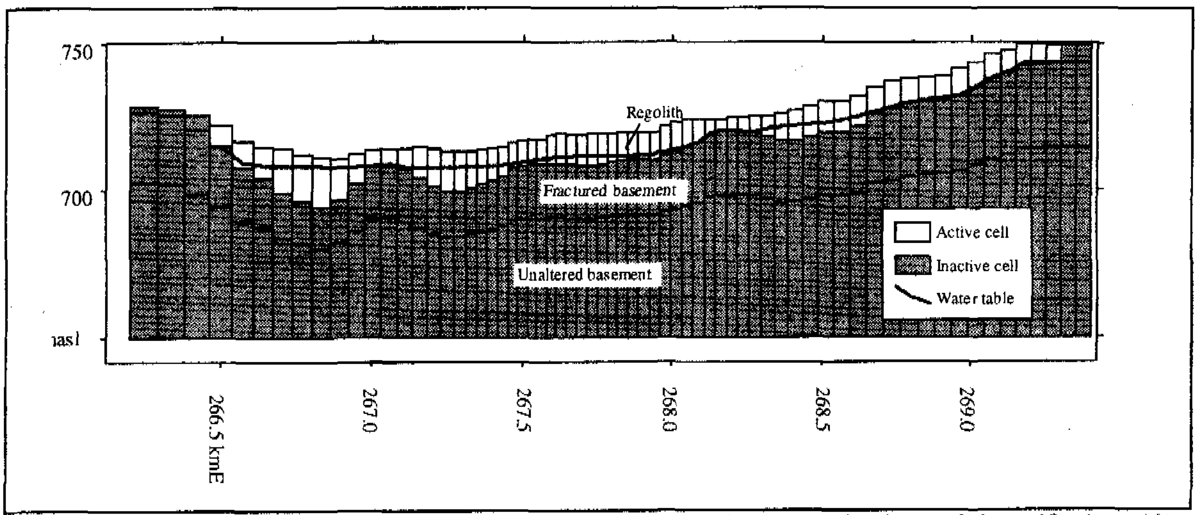

Figure 2. Longitudinal transect through model showing depth variation in regolith aquifer (row 19)

Assumption of 'no-flow' across groundwater divide

The catchment is bounded by no-flow cells representing the hard rock of the valley walls in all parts except in the northern and eastern extremities (see Figure 1). Both these areas are assumed to lie along the groundwater divide, and hence to represent no-flow boundaries. In fact for both this represents a simplification, in particular for the northern boundary where observed water table fluctuations suggested that while the groundwater divide was initially located on or about this area it shifted to the north after the 1995/96 season, when the water level reached a new (perhaps perched) level from which it has yet to decline. To the east the broken record of the piezometers monitoring the water table at the upper end of the catchment suggests that the groundwater divide has remained in this region throughout the modelling period.

Assumption of evaporation occuring at potential

An important assumption is that evaporation takes place at full potential. In addition, for deep rooted evergreen vegetation it was set at one and a half times potential. This reflects advice to the author (Batchelor, pers. comm.), and findings from other studies that suggest that in tropical drylands it is lack of water that acts as the control rather than evaporative demand (Calder, 1999). One report of eucalyptus trees with their roots in a shallow water table found them abstracting as much as 3,600 mm/year in an area of 800 mm annual rainfall (Greenwood et al, 1985; cited in Calder, 1999). Both values are nonetheless high and essentially mean that it is left to lack of water to limit evaporation.

Potential evaporation was calculated using output from the automatic weather station, averaged over three monthly intervals to reduce the total number of timesteps necessary. Modflow deals with evaporation by allowing it to take place on a sliding scale between two user defined limits. At the upper limit (in this case of the top of the surface layer) evaporation occurs at full potential, at the lower limit (extinction depth) it ceases to take place (Figure 3). For the bulk of the model extinction depth was set at 2m, while for areas of deep rooted vegetation it was set at 9m. Both figures are fairly arbitrary, although the Modflow literature suggests 6-8ft (2-2.7m) as the normal depth for crop water use (McDonald & Harbaugh, 1988), while studies in India have shown that eucalypts were actively using water form at least 8m depth (Calder, 1999). In addition a value of 9 m was chosen for the cut-off depth to ensure that in areas where deep rooted vegetation existed evaporation could take place throughout the profile.

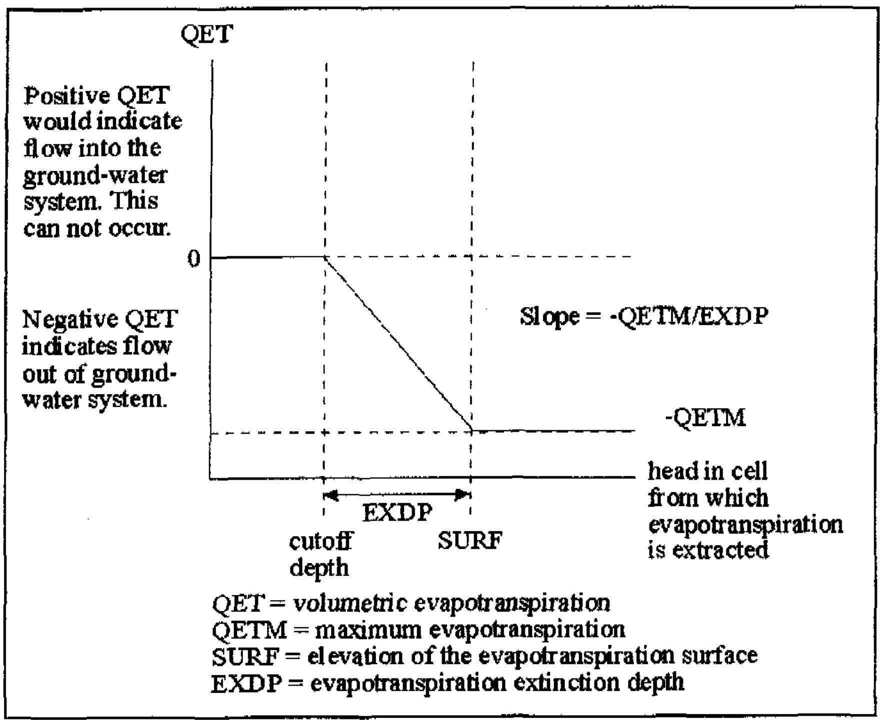

Figure 3. Evaporation as modelled in Modflow (after McDonald & Harbaugh, 1988)

The assumption of constant potential evaporation makes sense within this framework, as it will only occur where there is water within the cut-off zone, and observation has shown that grass and vegetation in low lying areas has in fact remained green throughout the wetter years since 1995/96. Figure 4 shows the distribution of deep and shallow evaporation within the model. This was derived from aerial photographs and ground truthing. However, it remains approximate.

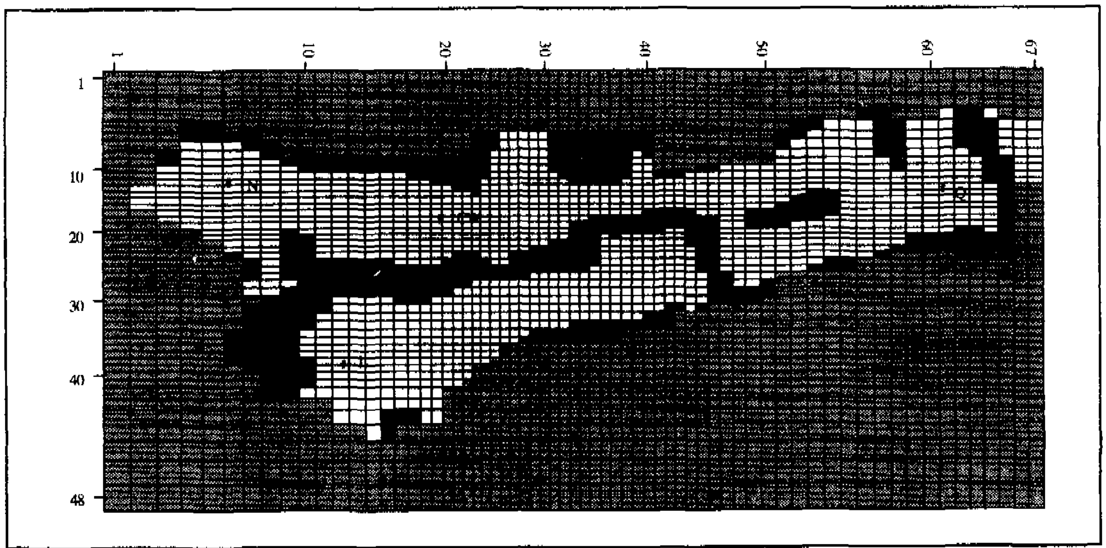

Figure 4. Area of deep rooted vegetation within the model (dark shading)

Callibration and sensitivity analysis

Callibration methodology

The test of any model is its ability to approximate real world observations, or at least those aspects of real world observations that are of interest to the user. In the case of the catchment aquifer two aspects were of primary importance. The first was to develop a water table that was at least approximately similar to that found by observation, and which en mass seemed to show similar types of behaviour to those observed. The second was to try and replicate the behaviour seen in a number of key observation piezometers.

Callibration results

The comparison of observed to modelled head is the standard way of assessing model behaviour (Anderson & Woessner, 1992), and this was carried out over a range of values for all key parameters to assess model sensitivity to parameter change. Horizontal conductivity (K_h) was varied from 0.1-10 m/day, with vertical conductivity (K_v) set to 1/10th of this (although as the model ended up being largely two-dimensional this parameter ceased to have any importance). Specific yield (S_y) was varied between 0.5 and 0.01, and a number of different evaporation configurations were also tried. Figure 5 shows a comparison of observed head at the N6 piezometer to modelled data for eight test scenarios. In this case the data is from a recession analysis following high water tables immediately following recharge in the 1995/96 season.

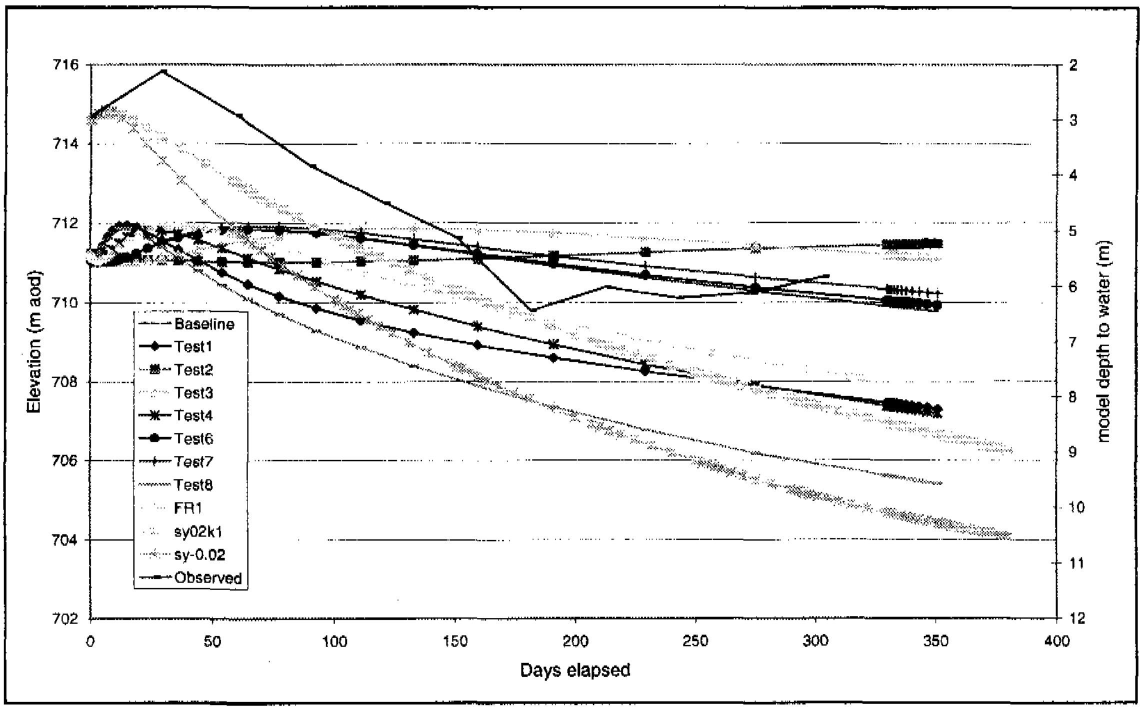

Figure 5 Sensitivity of recession curve to different combinations of K and S_y parameters for observation well N6.

The analysis allowed an envelope of the most successful parameters to be identified, with K_h ranging from 1 to 2m/day (and K_v from 0.1-0.2), and S_y from 0.02 to 0.05. Although with S_y set to 0.05 good results for some observation points were achieved with K_h as high as 5m/day, it was found that very similar results were achieved using K_h = 2m/day with S_y = 0.02. All these values fall within the range suggested by the findings in other components of the PhD study and general 'textbook' figures (Shaw, 1994: p. 138; Todd, 1980: p. 38 & p. 71). In general the value of K dominates the hydraulic gradients, while S_y dominates the overall water table level. A K that is too high will see quick development of a flat water table in the lower lying areas of the model, as water drains at unrealistic speed. Similarly a low S_y will see the water table rise or recess unrealistically in response to recharge or abstraction.

Figure 6 shows the modelled versus observed water levels at two observation wells (N6 and CW, CW being the collector well). This figure represents one of a great many developed for different permutations and combinations of possible parameters. In this case the average specific yield reported at the start of the paper was used (S_y = 0.036), with K_h = 2m/day. As part of the reason for using the model was to test the high values found for recharge, a number of modelling experiments were carried out with varying recharge values. For the experiment whose output is shown the estimated recharge values reported at the start of this paper are also used (24 mm, 188 mm, 147 mm, and 133 mm – Table 1).

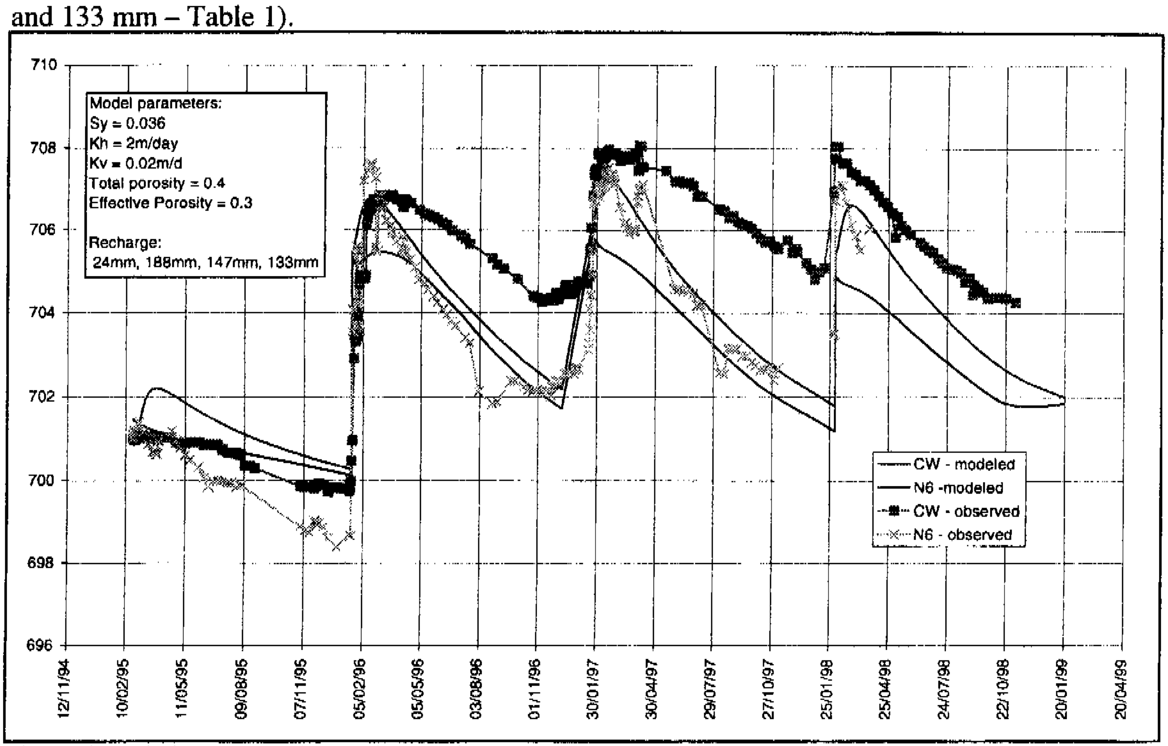

Figure 6 Modelled versus observed groundwater behaviour over four years

The model represents behaviour somewhere between that of the two observation piezometers, but closer to that of the N6 piezometer. It does not replicate the full range of fluctuation seen at N6, but at the same time it over-exaggerates that seen at the CW. This failure is due to a number of causes: firstly, the rate of evaporation in the valley floor is probably too high; secondly, enhanced recharge experienced at the N6 due to runoff from the Romwe inselberg and other impervious surfaces is not reflected; and thirdly, and probably most importantly, due to the previously discussed problem of Modflow not allowing re-wetting, the true temporal distribution of recharge is not achieved.

In a year when recharge is caused by one or two intense rainfall events modelling recharge as a single injection of water into the system is acceptable, however when as was the case in 1996/97 it takes place over an extended period this is not satisfactory. Figure 7 shows water table behaviour at three piezometers and the rainfall causing it. Rainfall is represented as a moving five day total – rainfall totals were tried for a number of time periods (five, ten, fifteen days), but the five day total showed the best correlation with water table behaviour. While the major rises in water levels are caused by clearly identifiable peaks in rainfall, it is equally clear that in the years since 1995/96 the decline of the water table has halted considerably before the main rise takes place. This represents less dramatic recharge taking place over extended periods, and it is this that is completely missed out by the model. Comparing modelled and observed rates of recession during the dry season, it can be seen that the model manages a reasonable approximation of observed behaviour.

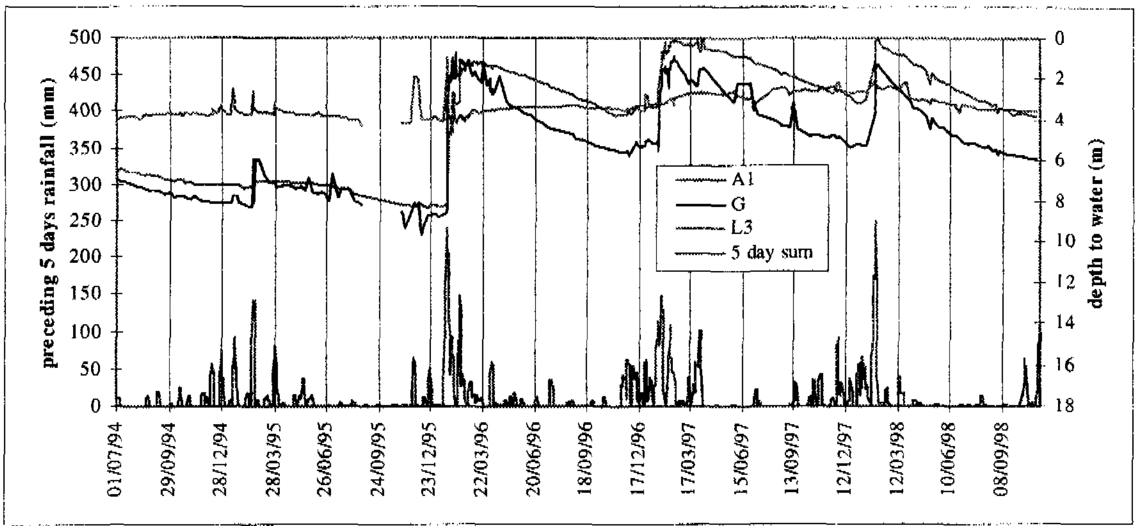

Figure 7 Water table fluctuations at three piezometer stations (A1, G and L3) and rainfall totals (5-day sums)

In a less heterogeneous landscape than that of the Romwe catchment these results might be seen as giving an unacceptably poor fit (although Gore et al (1998) published similar results from a complex aquifer in India). Bearing in mind the many simplifications made in the model, and that the model does not represent Romwe so much as a 'Romwe-type catchment' (with highly concentrated rainfall) the results are acceptable. It is clear that the use of a single value for key parameters (K_h, S_y and recharge) is not correct, leading to some rises being over-exaggerated while some are under-estimated. Nonetheless a reasonable approximation of system behaviour is achieved, and without greatly increasing model complexity it proved impossible to achieve better results.

Investigation of the groundwater resource of the Romwe catchment

Having managed to get an acceptable (though far from perfect) level of behaviour from the model, and to define an envelope of main parameters, the model was used to examine a number of fundamental scenarios regarding aquifer behaviour. As with the sensitivity analysis this scenario testing was done only in terms of its effect on the falling hydrograph, as the constraint of not being able to apply recharge remained.

As mentioned at the start of the paper, two elements were of prime concern. Firstly values of recharge and discharge was investigated; and secondly the natural recession found across the catchment was modelled to see if it could be explained in terms of water leaving the catchment through either use by vegetation or drainage to deep fractures in the basement. As part of this part of the investigation the probable effects on groundwater available for other productive uses of increasing the area of deep rooted vegetation was investigated.

In addition, once an acceptable level of model behaviour had been achieved, another important use of the model was to examine the effects of the abstraction from the catchment collector well, particularly in terms of its effect on the groundwater table in periods of extended low recharge, and of possible development scenarios based on introducing more small scale irrigation schemes to the area.

Spatial distribution of groundwater storage potential: the effects of geological variability

The main thing that becomes clear from the model's behaviour is the importance of 'sump points', lower down in the catchment, where groundwater collects and pools. There are two important zones of this type in the north-west catchment, separated by a ridge of impermeable rock. One is immediately under the Romwe inselberg, and runs down towards the catchment stream before being blocked by the central ridge; the other lies in the saddle between the Romwe and Barura hills, and contains the collector well in addition to some of the most productive private wells and irrigated gardens just outside the catchment boundary. Figure 8 shows the two zones highlighted on the map of the catchment. The two areas can also be clearly seen in the longitudinal slice through the northern part of the catchment as represented in the model shown in Figure 2.

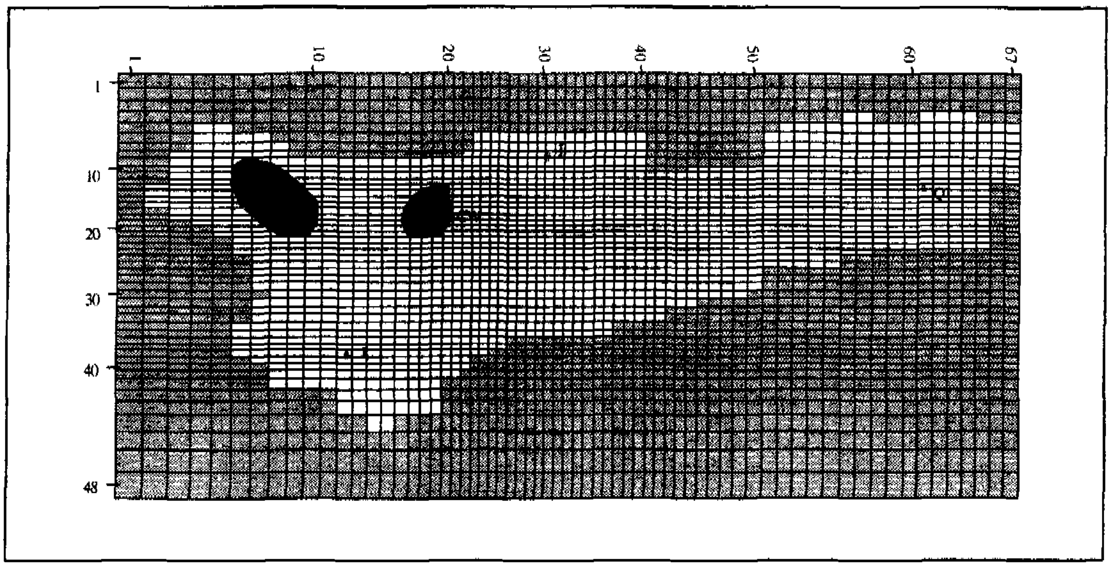

Figure 8 Map of catchment with two main zones of deepest weathering

The partition of groundwater discharge and the relative demands of abstraction by humans and deep rooted vegetation

In all of the simulations groundwater abstraction by humans (as modelled by a single well in the same location as the collector well) was insignificant when compared to that by vegetation/evaporation. In addition, and despite several attempts it was impossible to produce a realistic scenario in which groundwater was being drained from the system through a series of deep fissures. Modflow is not designed to model fissure flow, as it is based on the Darcy equation for flow through a porous medium. Nonetheless it is possible to simulate a fractured zone to some extent by assigning a high conductivity and low storage to series of connected cells. However, when this was tried, it was impossible to replicate the pattern of catchment wide water table behaviour seen in reality – the system tended to empty out through the area connected to the fissure system leading to a pattern of sharp drawdown towards that area (or the complete emptying of the system if regolith K was set to a high value).

While the model does not truly represent the south-western section of the catchment due to the lack of duplex soils, it is interesting to note that the presence of deep rooted vegetation leads to a rapid drying out of the area immediately beside catchment surface water outlet. This demonstrates that it is not in fact necessary to have a system of deep cracks or fissures in the hard rock to be able to explain the lack of baseflow leaving the catchment through the stream.

Given that it is the only hypothesis that can replicate even roughly the observed behaviour of the water table, the model gives reasonable support to the hypothesis of water use by vegetation as being the primary driver of water table behaviour. With this model it was impossible to replicate behaviour conversant with the catchment being joined to groundwater systems further downstream in the larger catchment.

Once the model had been successfully developed and tested for existing deep rooted vegetation, and with the layer incorporating the fractured bedrock made inactive (i.e. with a two-dimensional model) the model was run once again with the whole aquifer area covered with deep rooted vegetation. A much faster drawdown resulted, with most of the system drying out within 290 days and water remaining only in the deeper collection points.

Effects of existing and possible future abstraction on the groundwater resource

To investigate the effects on groundwater of existing and possible future abstraction the same model used in the previous section was utilised, with initially one and then up to 10 pumping wells located in the two zones of maximum depth of weathering (Figure 8). The first well was placed in approximately the position of the existing collector well. Initially abstraction from the single well was modelled for 15m^3 and 30m^3 per day, showed a barely perceptible effect at $S_y = 0.05$ while at $S_y = 0.02$ and an abstraction rate of 30m^3 per day it caused localised de-watering after 200 days.

Figure 9 shows a cross-section through the relevant section of the model in which the steep drawdown typical of a basement aquifer may be seen – with the well failing despite a generally high water table. This is precisely what happened in the 1991/92 drought when abstraction had to be reduced to prevent drying out (Lovell, pers. comm.), and at the end of the 1995 dry season when the well was pumped dry twice a day and then allowed to recover. The advantage of the collector well system is that by allowing recharge from a much wider area the permeability constraint around the well walls may be at least partially overcome.

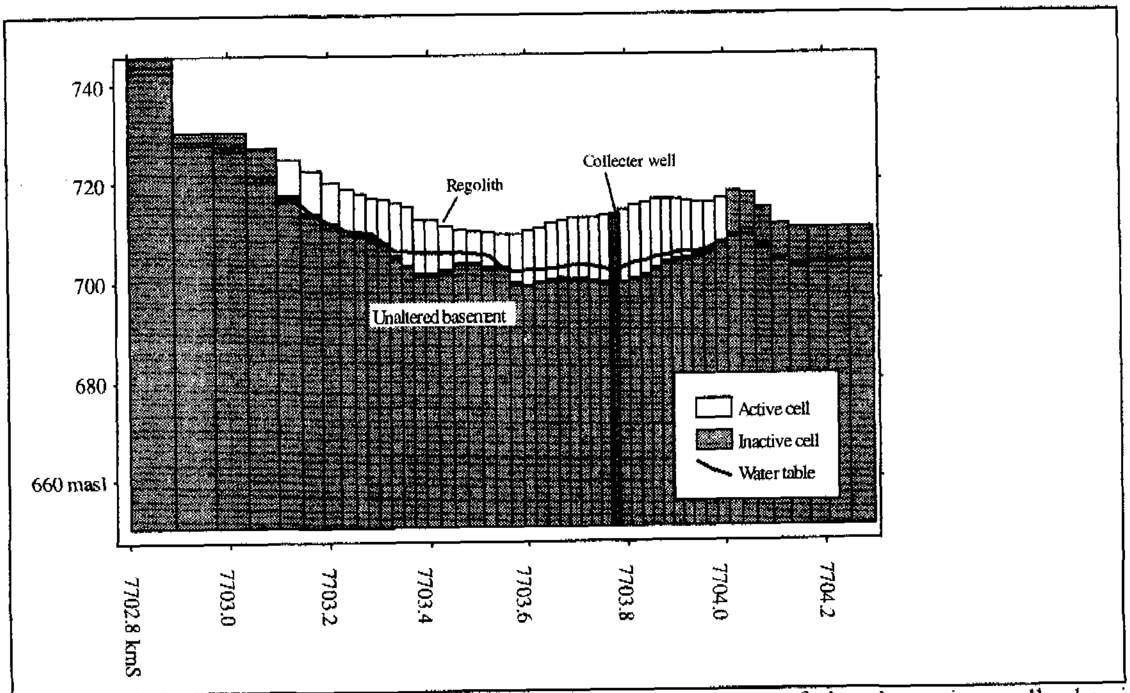

Figure 9 Longitudinal cross section through the model in the zone of the abstraction well, showing local dewatering due to low permeability (column 17)

In the second series of tests nine extra wells were added to the model (six in the deep zone surrounding monitoring point N, and two surrounding the collector well, Figure 8), at the lower pumping rate of 15m^3/day (mimicking the abstraction of existing collector wells) and with S_y set at either 0.05 or 0.02. With S_y at 0.05 only one well failed in the 380 day test period, and then only after 250 days of constant pumping, and due largely to poor siting. However, with $S_y = 0.02$ all except one of the wells failed, the first after only 150 days pumping, and most of the rest after 290.

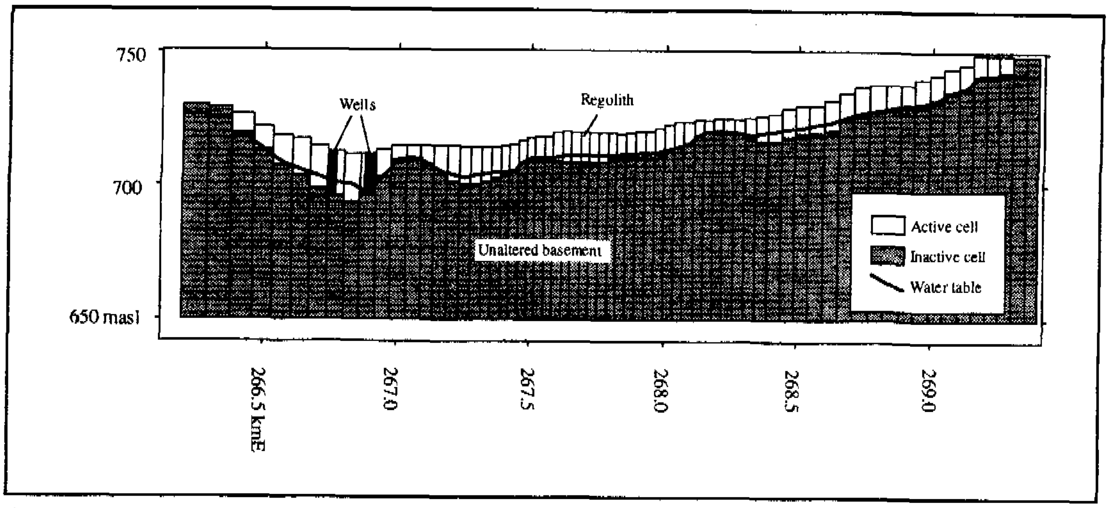

Figure 10 Drawdown due to a field of collector wells (row 18)

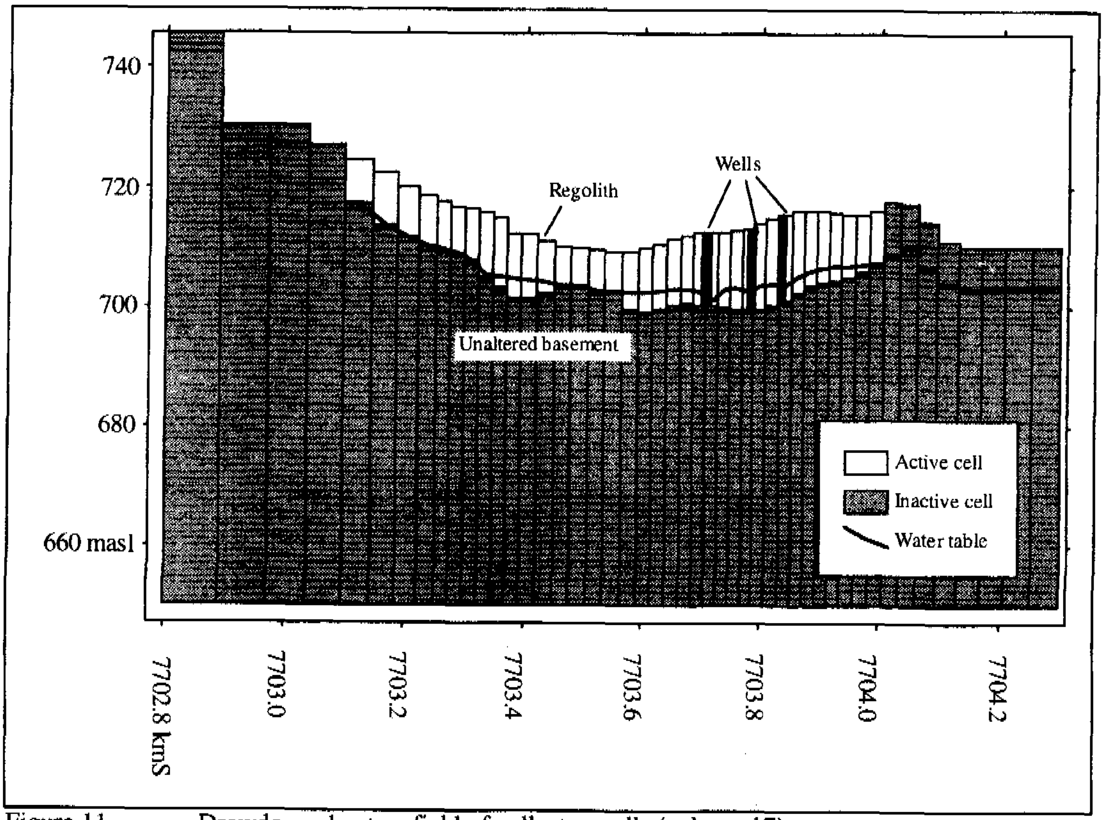

Figure 11 Drawdown due to a field of collector wells (column 17)

Figure 10 and 11 show a transverse and longitudinal section through three wells, showing the steep cones of depression formed due to over abstraction. In this particular example $S_y = 0.05$ but forest cover (deep rooted vegetation) has been modelled as occuring across the catchment; the transects are taken after 200 and 290 days respectively. Two of the wells in column 17 had failed by 290 days, although the central well (the existing collector well) lasted another 40 days.

Discussion of the modelling exercise and its results

The success or failure of the model to assist understanding of catchment processes.

The use of the groundwater model had distinctly mixed results. On the negative side it failed to deal adequately with the complexity of the system, notably in being unable to model the dynamics of the grey duplex soils. While this was an important failing in terms of validating the conceptual model of the catchment, it was less so with regard to quantifying the groundwater resource of the catchment given that recharge in these areas is minor compared to that of the red soils.

The greatest weakness was the inability to introduce recharge into cells that had previously gone dry without having to resort to the clumsy expedient of using additional code written within the GIS. This more than any other failing makes Modflow in its current format unsuitable for modelling shallow crystalline aquifers. While it was outside the scope of this work to write additional code for the model, this is undoubtedly what should be done if the model is to be further developed for basement aquifer use.

Linked to this is the inability of the model to sensibly deal with recharge excess: a much commented on failing of Modflow is its inability to 'know' when cells in the upper layer of a model have overtopped. Given the existence of general head boundaries which act as infinite sources or sinks it is a major flaw that the model does not have the ability to allow the top of the surface layer to act in a similar way, thus in effect modelling saturation excess runoff.

These obvious drawbacks aside, the model was still useful in developing and to some extent validating a conceptual model of the functioning of the aquifer in the deeper red soils of the north and south-west parts of the catchment. These are in any case, from a water resource point of view, the most interesting (due to their freely draining nature). The model has given solid backing to the logical integrity of the conceptual model of how this system works. In particular it has strongly supported the role of vegetation, both deep and shallow rooted, as being the major control of water table recession. This is a valuable and important finding, as it has profound implications for the management of groundwater resources.

The model gave equally strong support to the development of further productive water points in the catchment, showing that these would be at least as sustainable as the existing collector well. Given that a collector well is designed to irrigate half a hectare and is assumed to need a sustainable abstraction of 15m^3 per day, it is suggested that up to a further 5ha could be irrigated in the zones of groundwater accumulation shown in Figure 8 using either collector wells or large diameter wells.

A further useful application of the model is as a didactic tool to help demonstrate the behaviour of wells and boreholes in crystalline basement aquifers. The concept of well failure due to low transmissivity rather than to lack of water, and despite an otherwise high 'regional' water table, is important in understanding the mechanisms of crystalline basement aquifer behaviour. The fact that the modelled behaviour of the collector well was similar to that observed in 1994/95, where temporary failure was a daily occurrence, is instructive. In addition the model can be used to demonstrate the highly uneven distribution of water resources, and the reason why many family wells will fail late in the dry season as the water table falls. Conversely it can demonstrate how properly cited high yielding communal water points can draw on the pooled resources of 'sump points' to give adequate water for domestic and productive use.

The role of ground and surface water from Romwe in the larger Runde catchment

The support of the model for the hypothesis that the main cause of observed groundwater recession is vegetation, if found to be more widely true, has profound implications for the understanding and management of the groundwater resource at a larger river basin scale. It would seem to suggest, for example, that the contribution of groundwater recharge to river base flows will be negligible for all but those micro-catchments closest to the rivers. It also suggests that, apart from at the micro-catchment scale, there will be negligible effects from change in land use on groundwater resources further downstream. Even within the micro-catchment there is no guarantee that managing one section will have an effect on the groundwater of another. Each catchment needs to be examined and treated for its own unique range of soils, geology and topography.

Scaling up: given knowledge of the heterogeneity encountered in the Romwe catchment, is this possible, and what are potentially successful approaches?

Given the effort in time and resources put into developing the groundwater model of the Romwe aquifer – and the mixed results gained, it is difficult to see how the approach of using a distributed groundwater model would be of much use in terms of general 'scaling-up'. The complexity of the basement means that entirely local effects control a highly localised aquifer.

Earlier in this paper the metaphor of an iced cake was used to describe the relationship between water table and topography. Perhaps a more suitable image is one of rock pools – in which the residue of the departing tide (or rainfall) is left to slowly evaporate away until replenished by the next high tide (or rainy season). Each rock pool is an entity in its own right, disconnected from others on the same shore line, each one wholly responsible for sustaining its own ecological community between inundations. To talk about groundwater as a shared resource at a river-basin scale in such a framework is meaningless. It is a wholly local resource, common only to those people living in the immediate area, or micro-catchment. In a way, this lends it to a highly localised common property resource management approach – decisions on runoff control measures, forestry or irrigation will have a wholly local effect and as such should be easily understood and made relevant to local communities' livelihoods.

In retrospect it may well be that Modflow was not the most appropriate tool to look at the water resources of the shallow basement aquifer. Certainly, there is no evidence in the literature of it having been used to model crystalline basement aquifers in other parts of the world. Nonetheless, following extensive enquiries amongst groundwater experts no advice on a better approach was forthcoming, and while Modflow had not been used specifically for shallow crystalline basement aquifers in semi-arid regions before, there are numerous examples of it being used to model shallow phreatic groundwater systems (see, for example, Jiansheng Yan, 1994). With hindsight it is clear that the main problem was the inability of the model to allow re-wetting through recharge once cells had gone dry, and if the model is to be used in future simulations the code must be changed to allow this.

In addition to changing the code to allow re-wetting, for modflow to be a truly useful tool for the sort of work reported here it needs both proper GIS based pre and post processing ability, and the ability to batch process Montecarlo simulations of large combinations of different parameter values. While examples do exist in the literature of integrated GIS and groundwater models, they are few and frequently do not go beyond the level of Visual Modflow in terms of functionality (Sunday Tim, et al., 1996; Orzol and McGrath, 1993).

Otherwise, while less than optimal, the results from the modelling exercise must be seen as having been useful. They have clearly demonstrated that the conceptual picture of how the groundwater system works in the freely draining soils of the 'red soil' areas of the catchment is sound. They have also shown that groundwater recharge is indeed high, but largely lost to recession, which this work strongly suggests is due to abstraction by deep rooted vegetation. It has further confirmed within reasonable limits of certainty that the 'Romwe aquifer' - in as much as it exists - is largely isolated from the larger catchment downstream. Finally, it provides a potentially useful tool for demonstrating to non-specialist audiences the fragmented nature of the groundwater resource, and how this in turn will effect water supply and management options.

Conclusions

The key conclusions from the modelling work are as follows:

- Modflow can be used to model shallow crystalline basement aquifers, providing that the system is not too discontinuous, and that the regolith can be treated as being relatively homogenous. To be a truly useful tool, however, it would need modules to allow it to deal with recharge to cells that have gone dry and an ability to allow saturation excess run-off.

- The fluctuations of the crystalline basement aquifer of the Romwe catchment may be satisfactorily explained in terms of water use by vegetation without the need for drainage to 'deep fissures' to be taken into account.
- The Romwe catchment may be considered a closed system as far as groundwater is concerned, with no evidence of drainage to downstream areas.
- A range of aquifer parameters can produce acceptable results in terms of overall model behaviour, with specific yield varying between 0.01 and 0.05, and conductivity between 2m/day and 5m/dya. The model supported both the specific yield (0.036) and recharge/discharge estimates made using a water balance methodology. Using these values of specific yield and recharge implied an aquifer wide conductivity of 2m/day.

References

Anderson, M.P., Woessner, W.W., 1992. Applied Groundwater Modelling – Simulation of Flow and Advective Transport, Academic Press Inc., 381pages

Butterworth, J.A. 1997. The hydrology of a dryland catchment in southern Zimbabwe and the effects of climatic and land use change on shallow groundwater resources. Unpublished PhD Thesis, Department of Soil Science, university of Reading, UK, 241 pages

Calder, I.R. 1999 The blue revolution - land use and integrated water resources management, Earthscan,. London, UK, 192 pages

Carter, R.C., Morgulis, E.D., Dottridge, J., Agbo, J.U. 1994. Groundwater modelling with limited data: a case study in a semi-arid dunefield of northeast Nigeria, Quarterly Journal of Engineering Geology - Special edition, The Geological Society, Vol. 27, pp 85-94

Diodato, D.M. 1998. The Modflow Help, Software Spotlight - Groundwater, Vol. 36, No. 1, p3 the Modflow help file can be found at http://www.mindspring.com/~rvwinston/modhelp.htm

Greenwood, E.A.N., Klein, L., Beresford, J.D., Watson, G.D. 1985. Differences in annual evaporation between grazed pasture and Eucalyptus species in plantations on a saline farm catchment, *Journal of Hydrology*, Vol. 78:. 261-278

Gore, K.P., Pendke, M.S., Gurunadha Rao, V.V., Gupta, C.P. 1998. Groundwater modelling to quantify the effect of water harvesting structures in Wagarwadi watershed, Parbhani district, Maharashtra, India *Hydrological Processes*, Vol. 12, pp 1043-1052

Jiansheng Yan, Smith, K.R., (1994) Simulation of integrated surface water and groundwater systems - model formulation. *Water Resources Bbulletin*, Vol. 30(5), pp 879-890

Lovell, C.J., Butterworth, J.A., Moriarty, P.B., Bromley, J., Batchelor, C.H., Mharapara, I., Mugabe, F.T., Mtetwa, G., Dube, T., Simmonds, L. 1998. The Romwe Catchment Study, Zimbabwe – Final Report - The effects of changing rainfall and land use on recharge to crystalline basement aquifers, and the implications for rural water supply and small-scale irrigation, IH Report DFID 98/3, Institute of Hydrology, UK

McDonald, M.G., Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Techniques of Water-Resources Investigations Report. Book 6, Chapter A1, USGS

McDonald, M.G., Harbaugh, A.W. 1996. User's documentation for Modflow-96, an update to the U.S. Geological survey modular finite-difference ground-water flow model, Open-File Report 96-485, USGS

Moriarty, P.B. and Lovell, C.J. 1997. Groundwater resource development in the context of farming systems intensification and changing rainfall regimes: A case study from south-east Zimbabwe, AgREN Network Paper No. 81b, ODI London

Moriarty, P.B., Cain, J.D., Lovell, C.J. 1999 Holistic development of natural resources in Zimbabwe: developing a multidisciplinary data archiving system to support integrated management, proceedings 2nd inter-Regional Conference on Environment-Water - Emerging Technologies for Sustainable Land Use and Water Management, Lausanne, Switzerland, Presses Polytechniques et Universitaires Romandes, CD-ROM

Orzol, L.L., McGrath, T.S., 1993 Summary of modifications of the U.S. Geological survey modular, finite-difference, ground-water flow model to read and write geographic information system files. Water resources bulletin. *American Water resources association*, Vol. 29(5), pp 843-853

Osiensky, J.L., Williams, R.E. 1997. Potential Inaccuracies in Modflow simulations involving the SIP and SSOR methods for Matrix Solution. *Ground water*, Vol. 35, No. 2, pp 229-232

Shaw, E.M. 1994. Hydrology in Practice, Third edition, Chapman & Hall, 569 pages

Sunday Tim, U., Jain, D., Hsiu-Huka Liao, 1996 Interactive modeling of ground-water vulnerability within a geographic information system environment. *Ground water*, Vol. 34, No. 4, pp 618-627

Todd, D.K. 1980. Groundwater Hydrology - Second Edition, Wiley

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