# Initial evaluation of a simple coupled surface and ground water hydrological model to assess sustainable ground water abstractions at the regional scale

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## ABSTRACT

Additional surface–ground water interaction routines were recently added to the Pitman monthly rainfall–runoff model, widely used in South Africa for quantifying water resources in ungauged catchments. Some evaluations of the model have demonstrated that it can realistically simulate interactions between surface and ground water at catchment scales of approximately 100 to 5,000 $km^2$. The model allows ground water abstractions to be simulated, but no reported evaluations of this component are available. This study uses the model to estimate sustainable abstraction volumes in a semi-arid catchment and includes an assessment of model parameter uncertainties. In recognition of potential spatial scale issues related to the model structure an alternative model configuration, based on splitting the total catchment into recharge and abstraction sub-catchments, was also tested. While the results appear to be conceptually appropriate, there is insufficient available information to quantitatively confirm the model parameters and results. The same would apply regardless of the type of model being applied in such a data-deficient area. Additional geo-hydrological information is required to resolve the model uncertainties and improve the parameter estimation process. This pilot study has highlighted the type of information required, but further work is needed to identify how best to obtain that information.


**Key words** | ground water, hydrological models, recharge, resource estimation

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## INTRODUCTION

It has long been recognized that there is a need to integrate surface and ground water resource assessments in a country such as South Africa, where optimal management of all water resources is essential (Parsons 2004). This integration is hampered by problems such as a lack of observed data (for surface and ground water, as well as their interaction), a lack of understanding of the processes of interaction and the fact that different methods (models) of assessment have been traditionally used for surface and ground water. Surface water assessments in South Africa have largely been based on conceptual type rainfall–runoff models (Pitman 1973) that have previously included ground water components in a highly simplified way.

One of the results has been confusion between the baseflow output from the model (the slowly changing low-flow signal in the output time series) with real ground water contributions to stream flow (Le Maitre & Colvin 2008). It has been noted (Winter *et al.* 1998; Hughes 2009) that these will not always be the same and that baseflows can be derived from drainage processes acting in the unsaturated zone above the ground water table. The fact that the earlier versions of the Pitman model made no distinction between the sources of baseflow and that the process was poorly defined in the model also contributed to the confusion.

On the other hand, ground water assessments have frequently employed analytical (e.g. Butler *et al.* 2001) or

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numerical models (e.g. MODFLOW: Harbaugh & McDonald 1996). While such models have been used very successfully for detailed modelling, incompatibilities between these models and widely used surface water models (in terms of model structure and spatial scale) suggest that integration for regional scale modelling will always be very difficult. Many of the analytical and numerical ground water models are also highly data intensive, a problem that is difficult to surmount in a data-deficient region such as South Africa.

One approach to resolving the issue of integration is to incorporate more explicit (and conceptually appropriate) ground water routines into existing surface water models. The intention would be to provide a water resources assessment tool that is compatible with our conceptual understanding of catchment scale processes (both surface and ground water) and that can be applied with reasonable confidence given existing information. What level of confidence can be considered reasonable needs to be assessed with respect to the type of decisions that will be made using the model results. Quantifying the confidence can only be achieved through model testing and comparisons with real data (where available), outputs from other models that have already been tested or, at the very least, against our conceptual interpretation of reality. The authors are aware of other approaches that are currently being developed for South Africa (personal communication from R. Murray, 2008) but results are not yet available for comparative purposes. It is therefore recommended that comparative tests of all the methods should be a priority for the future, when the development of the individual models is complete.

The monthly time-step Pitman rainfall–runoff model (Pitman 1973) has been in practical use for the purposes of water resource availability estimation (Midgley *et al.* 1994) within South Africa for many years. It is a conceptual-type model with parameters representing the main storages and fluxes that constitute the natural water balance of river basins. Current versions of the model also include components that allow artificial impacts such as small farm dams, larger dams, abstractions and return flows to be included in the modelling scheme.

Hughes (2004) and Hughes & Parsons (2005) report on recent modifications made to the model, which focus on representing surface–ground water interactions in a more explicit way. The full model is described in detail in Hughes *et al.* (2006). These modifications, as well as an alternative approach (Sami 2006) to simulating surface–ground water interactions, have now been incorporated into the Department of Water Affairs and Forestry official version of the model that forms part of the WR2005 national database and analysis tools (Bailey 2007). Hughes (2004) and Hughes & Parsons (2005) introduced the revised model concepts and algorithms and reported on some preliminary tests. They concluded that the revised model structure is appropriate for simulating the ground water contributions to stream flow in different parts of South Africa but noted that appropriate simulation results can only be obtained with appropriate parameter values for the ground water algorithms of the model. Guidelines for the parameters of the surface water components are available from Midgley *et al.* (1994), while Kapangaziwiri & Hughes (2008) offer an alternative approach that is under development.

With respect to the parameters associated with the ground water components of the model, the Department of Water Affairs and Forestry GRAII database (Conrad 2005) provides estimates of storativity, transmissivity, maximum depth to ground water and annual recharge at a spatial scale (approximately 100 to 1,000 $km^2$) appropriate for typical model applications. Hughes (2009) applied the model in a semi-arid tributary basin of the Orange River and the results were in broad agreement with conceptual interpretations of the interactions between surface (stream flow and the maintenance of static channel pools) and ground water that were developed from limited field observations.

The revised model also includes simple algorithms designed to account for the impacts of ground water abstractions, but these have yet to be tested against either observations or conceptual principles. The objectives of this study were to determine if the ground water abstraction components of the model can be expected to generate realistic outputs, to identify the main sources of uncertainty associated with the use of the model and therefore to determine whether the model has the potential to contribute to assessments of the sustainability of ground water abstraction schemes at the catchment scale. It is important to note that it is not the intention of this article to suggest that this simple, catchment-scale model can replace detailed ground water investigations (either based on field observations or through the use of specialized ground water models).

## THE MODEL CONCEPTUAL STRUCTURE

Figure 1 provides a flow diagram of the main components of the revised model. A comprehensive description of all of the model components and algorithms (both original and revised, surface and ground water) can be found in Kapangaziwiri (2008) and a less detailed summary in Hughes *et al.* (2006). The conceptual foundation and mathematical details of the ground water component algorithms can be found in Hughes (2004) and Hughes & Parsons (2005).

The model is semi-distributed with each sub-catchment having its own rainfall and evapotranspiration demand time series and its own parameter set used to represent the main hydrological processes. The ground water components of the model are based on relatively simple geometry. The horizontal geometry is based on defining a number of channel segments and equal-sized slope elements. The number of slope elements and the width and length of each slope element are determined from the catchment area and a *drainage density* model parameter. The vertical geometry is defined by a simple representation of the ground water table in each slope element (Figure 2, left-hand column). The modelled ground water level is always attached to the channel (the small triangle at the base of each slope element in Figure 2) and is then defined by two line segments (near and remote from the channel). The near channel line segment is arbitrarily set as 40% of the slope element width and the remote segment as the remaining 60%. The horizontal line at the base of each diagram in Figure 2 represents the lower limit of the junction between the two line segments which is defined using a *rest water level* parameter.

The model estimates recharge through a modification of one of the original model components which is based on a *maximum monthly recharge* parameter, the status of the unsaturated zone storage and a non-linear power function. The recharge estimate is added to the ground water store (the area below the dashed line in Figure 2, left-hand side), while losses from the ground water store include riparian evapotranspiration at the channel margin (based on a

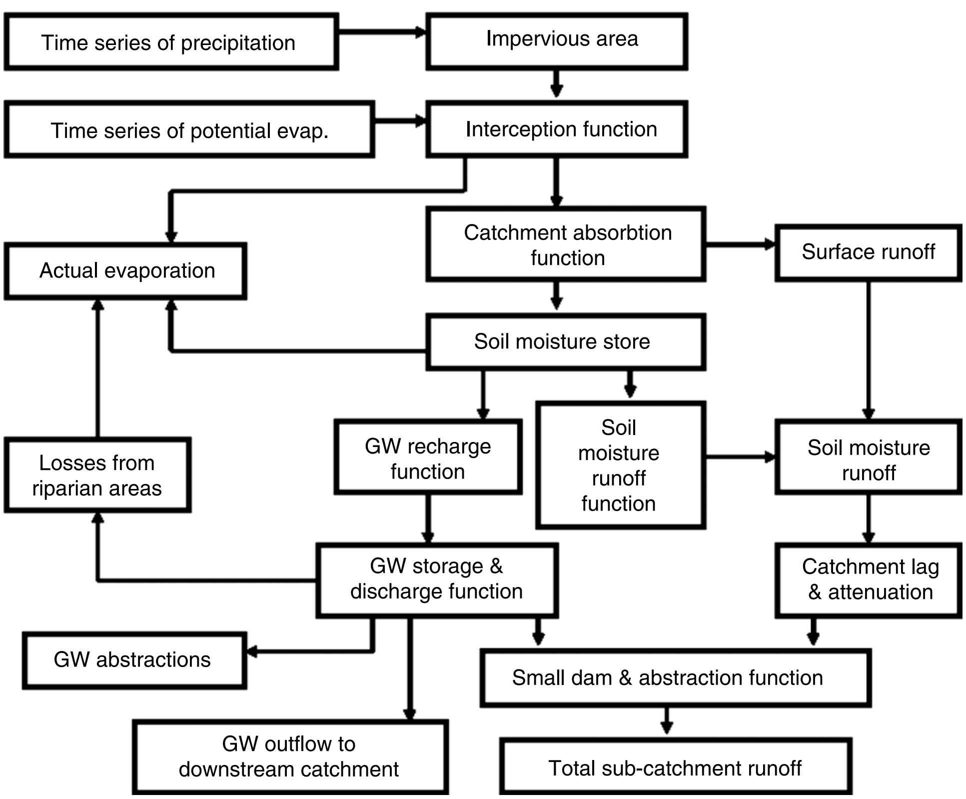


**Figure 1** | Conceptual structure of the revised Pitman model (including the ground water functions).

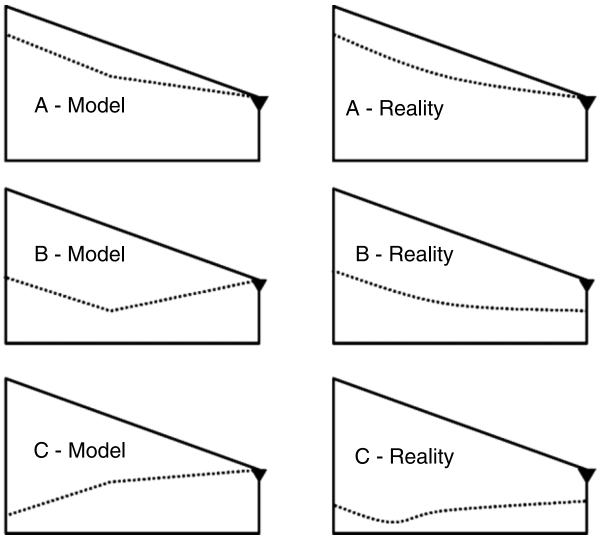


**Figure 2** | Modelled versus real groundwater conditions in a single hillslope element. Dashed lines represent the groundwater levels, the solid upper line represents the surface and the solid triangle represents the river channel. See text for explanation.

parameter specifying the proportion of the total slope element width that can contribute to losses, referred to as the *riparian loss* parameter), ground water discharge to the channel (based on the gradient of the near-channel line segment, a *transmissivity* parameter and the length of a slope element) and ground water flow to downstream catchments (based on a *regional ground water gradient* parameter, the *transmissivity* parameter and the slope element width). Water can also be transferred from the remote ground water segment to the near segment when the remote segment has a positive gradient. Water balance calculations (using a *storativity* parameter to translate water volumes into geometric volumes) are then used within each time interval of the model to update the gradients of the two ground water line segments. The first part of this process is based on the geometry of the near-channel segment, which fixes the position of the point joining the two segments, after which the gradient of the remote line segment can be determined by simple geometry.

Ground water abstraction parameters (annual volume and seasonal distributions) can be applied to the two ground water segments independently. Simulated abstractions are not limited while the point joining the two line segments is above the *rest water level*, below which abstractions are assumed to cease.

The essential assumptions of the model are that the ground water storage water balance is determined by inputs of recharge and outputs of flow to the river, riparian losses in the channel margins, drainage to a downstream sub-catchment and abstractions from boreholes. A further input component of channel transmission loss is added if the ground water level is below the channel and there is flow in the channel generated from the surface water components of the model. The ground water storage variations are therefore translated, through simple geometry calculations and the *storativity* parameter, into variations in the gradients of the two ground water segments. The variations in the gradients determine variations in the other water balance components. One of the reasons for adopting this approach, rather than attempting to calculate ground water depth, is that the model is operating at a relatively large spatial scale within which depth variations could be substantial. If the result of the water balance calculations were variations in a single sub-catchment representative depth, the approach for estimating some of the ground water output variables would be more complex and would probably have to account for additional factors that have not been included in the parameter set.

The right-hand side of Figure 2 interprets the modelled ground water slope geometry into the actual ground water conditions that the model is designed to conceptually represent. Figure 2A illustrates an example where both line segments have positive gradients and ground water will be contributing to flows in the channel (unless riparian evapotranspiration losses are higher than the lateral contributions). Figure 2B illustrates a situation where the ground water level is below the channel and no contributions to the channel are possible. This is reflected in the model as a negative near channel gradient. Under these circumstances the point joining the two ground water line segments will be below the level of the channel and this level is used to reduce both riparian evapotranspiration losses as well as downstream ground water flow. When this point reaches the defined *rest water level* (a parameter), riparian losses and downstream outflow are assumed to be zero.

Figure 2C illustrates a model situation where both gradients are negative, which is highly unlikely under natural conditions. The model includes a channel transmission loss function that allows channel flow to contribute to the near channel ground water segment when the near line segment gradient is negative. It is therefore theoretically possible that channel losses could result in a situation shown in Figure 2C. However, Figure 2C has been included to illustrate what could happen if abstractions occurred in the remote ground water segment at a rate that exceeded the recharge inputs. In reality, the result would be an extensive cone of depression around a borehole field, some distance away from the channel, and no movement of ground water towards the channel. Under this condition the model does not allow for water to be transferred from the near ground water segment, despite the fact that the gradient is in that direction. In reality, this is unlikely to happen to any great extent as the real ground water gradients close to the channel would almost certainly be very low.

It is accepted that the way in which the ground water dynamics have been conceptualized within the model will not be appropriate for all situations. Specifically, the model will not be applicable where large-scale primary aquifers dominate interactions with surface water, nor where confined aquifers play a major role. However, a very large part of South Africa is dominated by fractured rock systems where the relationships between recharge and ground water resources availability and the links to surface water operate at spatial scales similar to that at which the model is typically applied (of the order 100–1,000 km$^2$).

## THE STUDY AREA AND OBJECTIVES OF THE ASSESSMENT

Within South Africa there are no datasets that are available to explicitly test the ground water components of a model of this type and spatial scale of operation. Single borehole records are available for some areas, but these are strongly influenced by local draw-down and recovery associated with abstraction patterns. However, even in the absence of appropriate data, it is still necessary to make management decisions. The selection of the study area was therefore rather arbitrary and based on the fact that it represents the conditions found in many parts of South Africa where ground water abstraction decisions need to be made. The fact that there are no datasets immediately available suitable for thorough model testing is a cause for concern, and one that needs to be addressed as a matter of some urgency.

The study is based on semi-arid catchment L21E (712 km$^2$), a part of the Buffalo River in the Karoo region of the Western Cape Province (Figure 3). The town of Murraysburg lies within the catchment (in the bottom right-hand corner of the black rectangle in Figure 3). The underlying geology consists of horizontally interbedded shales, mudstones and sandstones of the Beaufort Series (Karoo System). The climate is semi-arid with a mean annual rainfall of less than 300 mm, potential evaporation of over 2,000 mm and an estimated runoff depth of 9.5 mm (Midgley *et al.* 1994). Rainfall and evaporation are expected to be relatively evenly distributed over the catchment at timescales of 1 month or greater, but will be far more variable at shorter timescales and related to localized convective storm activity.

The topography is undulating; soils are expected to be highly variable in depth and dominantly sandy-loams, while the natural vegetation is sparse karoo grassland and succulent bush. The GRAII ground water database (Conrad 2005) suggests that transmissivities will be of the order of 22 m$^2$ d$^{-1}$, storativity very low (0.001), rest water levels approximately 25 m below the surface and recharge 0.6–5% of rainfall. Experience in other semi-arid parts of South Africa with similar physical characteristics suggests that the

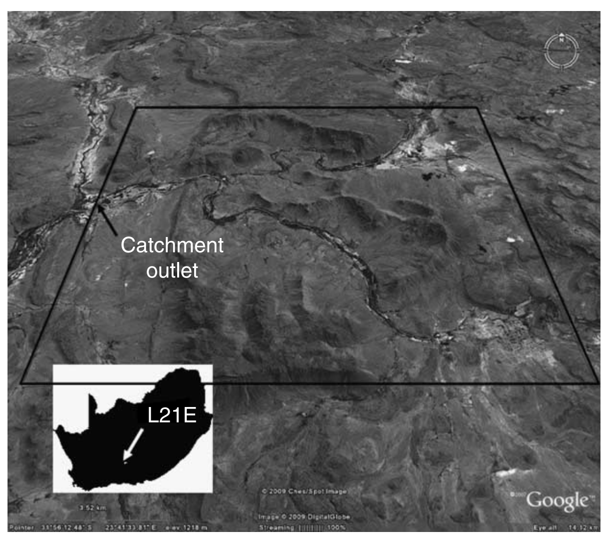


**Figure 3** | Google Earth image of the lower part of catchment L21E including an inset to show the location within South Africa. The image is tilted and the black rectangle represents an area of 250 km$^2$.

lower estimate of recharge is probably more realistic. The variations in aquifer characteristics will be dominated by variations in the size and density of fracture zones within the sedimentary rocks. The implication is that both recharge and ground water dynamics are expected to be highly variable across the catchment, while the model simulates average conditions.

The WR90 (Midgley *et al.* 1994) incremental flow data (based on the original version of the Pitman model with regionalized parameters) suggests that zero flow conditions occur approximately 25% of the time and that prolonged baseflows are absent. However, it is possible that ground water contributions to the channel occur some of the time, even in the absence of flow in the channel, and that they may contribute to sustaining static channel pools (Hughes 2009).

The objective of the modelling study was to determine if a realistic simulation of ground water conditions could be achieved and used to assess the extent to which different ground water abstraction volumes can be sustained. The problem in data-deficient areas is that identifying realistic (or behavioural) simulations is never an easy task, regardless of the model being used. An important part of the study was consequently the identification of the main uncertainties associated with the application of the model and how these influence the model results and therefore management decisions. The initial simulations treated the total catchment as a single spatial unit, while part of the uncertainty analysis involved dividing the catchment up into two spatial units to represent the main recharge and abstraction zones.

## INITIAL MODEL RESULTS

The model was established with standard inputs (rainfall and evaporation demand) based on the regional information available in WR90 (Midgley *et al.* 1994), as well as the WR90 recommended parameter values for the surface water components of the model. The ground water parameters were initially based on the GRAII (Conrad 2005) database, assuming the lower recharge estimate of 0.6% of mean annual rainfall. Calibrating the model to this recharge estimate resulted in a maximum monthly recharge parameter value of 15 mm. The resulting time series of surface runoff were more or less identical to those given for catchment L21E in WR90 (Midgley *et al.* 1994). Three abstraction scenarios were initially simulated and some of the ground water simulation results are presented in Table 1 and Figure 4. The ground water outflow (to downstream sub-catchments) variable is used in Figure 4 as a surrogate for the ground water level. If the outflow remains constant at a maximum value, the near channel ground water segment must have a positive gradient (based on the model structure). If the outflow reaches zero the simulated ground water level must have reached the rest water level, at which point the model assumes that abstractions are no longer possible. The recharge and outflow volumes can be interrogated from the model outputs while the remainder of the ground water balance, when there are no abstractions, is made up of evapotranspiration losses from the riparian zone.

**Table 1** | Simulated ground water balance components ($10^3\,m^3\,y^{-1}$)

| | | | |
|---|---|---|---|
| *Rest water level parameter set to 25 m* | | | |
| Design abstraction scenario | No Abstraction | $240 \times 10^3\,m^3\,y^{-1}$ | $900 \times 10^3\,m^3\,y^{-1}$ |
| Recharge | 1331 | 1331 | 1331 |
| Downstream outflow | 379 | 313 | 133 |
| Evapotranspiration | 952 | 778 | 322 |
| Actual abstraction | 0 | 240 | 855 |
| *Rest water level parameter set to 15 m* | | | |
| Design abstraction scenario | No Abstraction | $240 \times 10^3\,m^3\,y^{-1}$ | $740 \times 10^3\,m^3\,y^{-1}$ |
| Recharge | 1331 | 1331 | 1331 |
| Downstream outflow | 375 | 311 | 179 |
| Evapotranspiration | 956 | 780 | 449 |
| Actual abstraction | 0 | 240 | 703 |

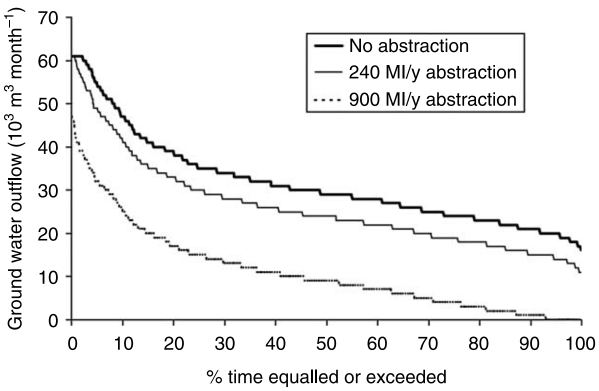


**Figure 4** | Duration curves of simulated (using a rest water level of 25 m) ground water outflow (to a downstream sub-catchment), used as a surrogate for ground water level (within the legend Ml = $10^3$ $m^3$).

The 240 × $10^3$ $m^3$ abstraction scenario was based on information about intended ground water abstractions in the catchment, while the 900 × $10^3$ $m^3$ abstraction scenario was established by trial and error to be the volume that can be sustainably abstracted 95% of the time (see Figure 4). In both scenarios, the abstractions were applied to the near channel ground water segment only, based on the assumption that most boreholes would be established in the lower-lying parts of the catchment. If the abstractions are applied equally to the two ground water segments (near and remote from the channel), the simulation results are almost identical.

## EVALUATION OF MODEL UNCERTAINTIES

The evaluation of hydrological modelling uncertainties and how these should be managed when using model outputs has been recognized in recent years as a critical field of research (Pappenberger & Beven 2006). A realistic assessment of model output uncertainty is clearly important because models are frequently applied for practical purposes in catchments where there are no observed data. A typical approach to evaluating uncertainty in the absence of observed data is to vary the parameter values over realistic ranges and assess the sensitivity of the model results to these parameter changes (Saltelli 2000).

The simulated volume of downstream outflow (28% of recharge under natural conditions) represents a large uncertainty in the modelling result for two reasons. The first is that the sub-catchment has been simulated in isolation and therefore receives no ground water inflow from other areas, while the second is that no information on actual sub-surface transfers of water is available. However, if the regional ground water gradient is reduced so that simulated sub-surface outflow is reduced to only 12% of recharge, the estimate of 95% sustainable abstraction remains at approximately 900 × $10^3$ $m^3$ $y^{-1}$. The water balance is maintained through greater evapotranspiration losses.

The sustainability of any given abstraction volume is clearly very dependent upon the rest water level parameter. The original model run used a value of 25 m based on the information contained within GRAII (Conrad 2005). However, the way in which this parameter is used within the model is possibly incompatible with the meaning of the aquifer thickness variable given in GRAII. The lower part of Table 1 therefore evaluates the effect of changing the rest water level parameter to 15 m. While the natural 240 × $10^3$ $m^3$ $y^{-1}$ abstraction scenario water balance components change very little, the 95% sustainable abstraction volume reduces to 740 × $10^3$ $m^3$ $y^{-1}$.

The evapotranspiration component of the ground water balance is extremely high and there is very little site specific information available about how much ground water may be lost through both terrestrial and riparian vegetation (see Colvin *et al.* 2003, however). The modelled losses are assumed to occur in the channel margin areas through either deep-rooted vegetation or through ground water seepage into the channel bed and banks (during times when the ground water level is relatively close to the surface) and subsequent evaporation. The extent to which these processes continue as the ground water level drops is largely unknown.

For a given recharge volume, the parameters of the ground water component of the model that have the greatest potential impact on the sustainable abstraction are the transmissivity, storativity, drainage density and riparian loss parameters. Estimation of appropriate values for these parameters will always be subject to uncertainty. Table 2 illustrates the effects of changing these parameters on the main water balance components (with recharge remaining constant at 1,331 × $10^3$ $m^3$ $y^{-1}$ and using a rest water level of 25 m). The results are based on using the initial values of the parameters except for those identified as having alternative values (i.e. the values are returned to their original values before changing other parameter

**Table 2** | Simulated mean annual ground water balance components for some alternative parameter configurations to illustrate uncertainty (using a rest water level parameter value of 25 m; see Table 1 for the output results based on the initial parameter values)

| Parameter and initial value | Alternative value | Downstream outflow ($10^3\,m^3\,y^{-1}$) | Evapotranspiration ($10^3\,m^3\,y^{-1}$) | Abstraction ($10^3\,m^3\,y^{-1}$) |
|---|---|---|---|---|
| Transmissivity (10.5 m $d^{-1}$) | 5 | 70 | 406 | 855 |
| | 20 | 235 | 336 | 760 |
| Storativity (0.001) | 0.002 | 91 | 271 | 969 |
| Drainage density (0.2) | 0.3 | 151 | 325 | 855 |
| Riparian loss parameter (0.15%) | 0.1 | 148 | 280 | 903 |
| | 0.3 | 101 | 518 | 712 |

values). The abstraction demand values were manually adjusted until a 95% level of supply assurance was achieved (e.g. the abstraction volume of $969 \times 10^3\,m^3\,y^{-1}$ in Table 2, row 4, represents an abstraction demand of $1{,}020 \times 10^3\,m^3\,y^{-1}$).

Uncertainty in the transmissivity parameter has a relatively small impact, despite the fact that this partly controls the volume of water transferred out of the sub-catchment. The effect of changing the transmissivity parameter value is very similar to changing the regional ground water gradient, in that both determine the downstream outflow. Any changes in downstream outflow are partly balanced by changes in evapotranspiration losses. Doubling the storativity (the GRAII recommended value is lower than the 0.001 parameter value) has quite a large effect and increases the sustainable abstraction volume quite substantially. Changes in the drainage density parameter were not expected to have a major effect in this type of situation as this simply affects the conceptual geometry of the sub-catchment. However, it has been previously noted that changes to this parameter can substantially affect ground water contributions to baseflow in regions with much greater recharge. The final parameter that was included in the uncertainty assessment (the riparian loss factor) largely controls evapotranspiration losses from ground water and, conceptually, these are considered to take place predominantly along the margins of river channels. Table 2 suggests that the model is quite sensitive to changes in this parameter value and that it may be very important to obtain an independent assessment of likely ground water losses to evapotranspiration.

While many of the parameter uncertainties have a substantial impact on the estimates of sustainable abstraction, they could be resolved if sufficient field information was available to approximately quantify the appropriate water balance components. The uncertainty problem is therefore associated less with the structure of model and more with the difficulties of estimating appropriate parameter values given currently available information. This is consistent with conclusions reached by other groups applying hydrological models in ungauged basins, and emphasizes the need for information that can be used to constrain parameter values (Yadav *et al.* 2007).

## AN ALTERNATIVE MODELLING APPROACH

Simulating the complete catchment as a single unit represents a further source of uncertainty (a scale issue). Under this configuration all of the recharging water is almost immediately available for abstraction, while in reality the major recharge zones (hill tops, where soils are expected to be thinner) could be remote from the areas where abstraction is expected to dominate (lower slopes and valley bottoms). The delays in the recharge water reaching the sub-surface storage zones where abstractions take place might be expected to increase the drawdown impacts of pumping, and therefore decrease the sustainable abstraction volume.

To assess whether the model can be used to simulate the effects of the spatial separation of recharge and abstraction zones, two alternative modelling approaches were used. In both alternatives the model was established with two sub-catchments having different ground water parameters: a headwater sub-catchment representing the main recharge zone and a sub-catchment representing the lower parts of the catchment where abstractions are expected to occur.

**Table 3** | Simulated ground water balance components for the two alternative model configurations

| | Recharge area = 30% of total area | | Recharge area = 70% of total area | |
|---|---|---|---|---|
| **Configurations** | **Recharge zone** | **Downstream zone** | **Recharge zone** | **Downstream zone** |
| Area ($km^2$) | 213.7 | 498.6 | 498.6 | 213.7 |
| Natural water balance components ($10^3\,m^3\,y^{-1}$ with no abstraction) | | | | |
| Recharge | 1173 | 160 | 1268 | 68 |
| Downstream outflow | 812 | 372 | 820 | 376 |
| Evapotranspiration | 361 | 600 | 448 | 512 |
| 95% sustainable abstraction ($10^3\,m^3\,y^{-1}$) | | | | |
| | | 720 | | 640 |

The first alternative assumed that the headwater sub-catchment covered 30% of the total area, while the second assumed 70% of the total area in the headwater sub-catchment. Both alternatives were re-calibrated to achieve the same overall water balance (i.e. same recharge and downstream outflow volumes) for natural conditions as those given in the top part of Table 1 (using a rest water level of 25 m). For the purposes of this simple exercise, the surface water parameters of the model were kept constant for both sub-catchments. The main differences between the ground water parameter values that were assumed for the two sub-catchments are summarized below:

- maximum monthly recharge parameter is assumed to be much higher for the recharge sub-catchment;
- gradient parameter, which controls downstream ground water outflow, is higher for the recharge zone;
- drainage density parameter is lower for the recharge zone; and
- riparian loss parameter is lower for the recharge zone.

Table 3 lists the natural water balance components for the two alternatives and the annual abstraction volume that could be sustained with 95% assurance. The results suggest that splitting the total catchment into two zones has a substantial effect, which increases as the recharge zone is made proportionally larger. Without further information about the real ground water processes that occur within this region, it is difficult to reach firm conclusions. However, the division of the total catchment into the two zones is conceptually sensible. It is encouraging that the model results are consistent with expectations associated with the effects (on sustainable abstraction volumes) of delays in recharge water reaching the sub-surface zones where abstractions are assumed to take place. With respect to some of the uncertainties already referred to, reducing the rest water level parameter (from 25 m to 15 m) has the effect of reducing the 95% sustainable abstraction volume by approximately $80 \times 10^3\,m^3\,y^{-1}$ for both model configurations.

Figure 5 illustrates the range of lateral ground water gradient conditions simulated by the model in the downstream abstraction sub-catchment for the second alternative (30% of the total area). The simulated gradients in this diagram should be interpreted using the same associations between the model and reality provided in Figure 2. Under natural conditions (Abs = 0) the remote ground water zone gradient is almost always positive, but becomes weakly negative immediately following large recharge events. This is something of a modelling artefact related to rapid changes

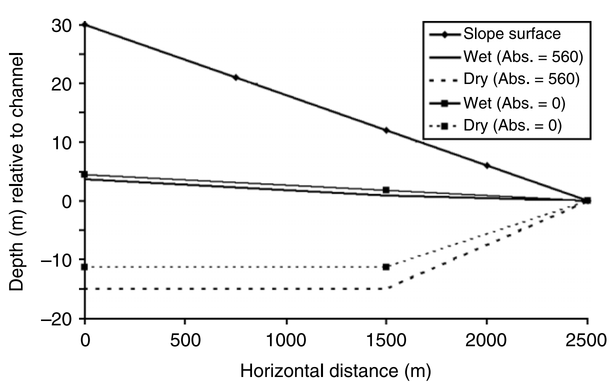


**Figure 5** | Simulated conditions in one slope element of the downstream sub-catchment (213.7 $km^2$) with a rest water level parameter value of 15 m and abstraction volumes of 0 and 560 $\times 10^3\,m^3\,y^{-1}$ (the slope surface line is arbitrarily positioned).

in the near channel zone gradient, but has no real impact on the ground water dynamics. The gradient close to the channel is almost always negative, but becomes weakly positive for about 12% of the time under natural conditions. With an annual abstraction of $560 \times 10^3$ $m^3$ $y^{-1}$, the wet conditions remain much the same as natural although they occur for shorter durations (about 5% of the time). Under dry conditions, the remote segment gradient is zero and the near segment gradient highly negative with the point joining the two segments at the rest water level. This equates to an extreme example of case B in Figure 2 where the real lateral ground water gradients will both be close to zero.

## DISCUSSION AND CONCLUSIONS

It is not suggested that the modelling approach presented in this paper is the answer to all the problems associated with the integrated development of surface and ground water resources. It is not designed to replace existing methods associated with smaller scale modelling, borehole tests and geophysical investigations used to site boreholes and determine pumping rates over short time intervals. The estimates of sustainable abstraction volumes do not, for example, account for any limitations related to the availability of suitable borehole sites, nor localized aquifer transmissivities and storativities that will affect sustainable pumping rates. Localized connectivity of ground water transmission zones (fractures) are also expected to play a major role in the yield of individual boreholes. The values for the majority of the ground water parameters used in the revised Pitman model have been derived from borehole records and pumping tests through the GRAII database. The use of the model presented here is designed to complement these approaches and to provide a link with established methods of surface water resources assessment. The model could also be used as a rapid, low-confidence assessment of regional ground water availability before more detailed geo-hydrological studies are undertaken.

While the specific example used in this paper is a semi-arid region where ground water contributions to stream flow are not considered important, the same approach could be used to assess the impacts of ground water abstraction on the low-flow regime of perennial rivers. In semi-arid areas ground water abstractions will mainly impact on static channel pool storage and riparian vegetation. While channel pool storage has not formed part of the model configuration for this example, a previous application in another ephemeral river (the Seekoei River; Hughes 2009) illustrated that the model is capable of simulating the dynamics of pool storage affected by both surface and ground water inflows. Table 1 includes the simulated evapotranspiration loss component under natural and abstraction scenarios. The model results suggest that maximizing abstraction volumes would have a very large impact on the availability of water to support riparian vegetation.

A further process that could play a role in the availability of ground water resources in semi-arid areas (especially where deep alluvial deposits exist) is infiltration from river channels during periods of stream flow. While the model does include a component to account for this process, it is extremely difficult to quantify. The catchment used in this study does not have extensive valley bottom alluvial deposits and therefore this process is unlikely to contribute substantially to the water balance of the aquifers.

In any application of hydrological models there are always sources of uncertainty related to model structure, input data and appropriate parameter values. Some of these sources of uncertainty are associated with scale issues and the extent to which a coarse scale model is able to adequately represent reality. It is recognized that hydrological (both surface and ground water) processes are highly spatially heterogeneous. Comparison of the initial results with the results from the alternative modelling approach presented above (dividing the total catchment into two subareas representing the zones of recharge and abstraction) illustrates that scale-related model structural issues could be extremely important and that these need to be investigated further. The authors consider that the most important source of uncertainty lies in estimating the values of some of the ground water parameters; this problem is difficult to resolve without further detailed information.

The GRAII database provides estimates of mean annual recharge that vary from 0.6% (used here) and 5% of mean annual rainfall. If the simulations had been based on the latter value, the result would have been substantial ground water contributions to stream flow (assuming most of the other parameters remain the same). This result is inconsistent with our understanding of the behaviour of this catchment based on existing information (Midgley *et al.* 1994). However, even a small increase from 0.6% would have resulted in a very different estimate of sustainable abstraction volume. The results presented have illustrated the effects of uncertainty in the estimate of rest water level, and reference has already been made to a potential mismatch between the interpretation of the source of this estimate (GRAII database) and the way in which it is used in the model. Additional uncertainty lies in the estimates of sub-surface movement of water between the modelled catchment and adjacent areas. One of the positive outcomes of the pilot investigation is a much clearer understanding of which parameters contribute the most to uncertainty in the results. This is important because it identifies where efforts to improve the parameter quantification will be rewarded by improved confidence in the model results.

The overall conclusion is that the model is able to simulate the interactions between surface and ground water and the effects of abstractions in a realistic manner. However, the values of the various simulated components of the ground water balance, as well as the estimate of sustainable abstraction volumes, are subject to a large degree of uncertainty. Resolving or reducing this uncertainty should therefore be the priority for further research. This uncertainty will always be present in such data-deficient regions, regardless of the type of model applied. If this uncertainty can only be reduced through comprehensive and expensive field investigations, the model (or any other model) may be largely redundant. However, if the uncertainty can be reduced by an improved interpretation of existing information coupled with limited field investigations, then it may be concluded that the model has a potential to contribute to integrated water resource planning and management. Perhaps one of the critical areas of future research is to determine what type of information can and should be collected to support the type of modelling approach discussed in this paper.

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