

Incorporating ground water recharge and discharge functions into an existing monthly rainfall-runoff model.

D A HUGHES

Institute for Water Research, Rhodes University, Grahamstown 6140, South Africa

E-Mail Denis@iwr.ru.ac.za

Abstract There is an urgent need for an integrated surface and ground water modelling tool that is suitable for southern African conditions and can be applied at various basin scales for broad strategic water resource planning purposes. The paper describes two new components (recharge and ground water discharge) that have been added to an existing, widely used, monthly time-step rainfall-runoff model. The application of the revised model on two basins in southern Africa with quite different baseflow characteristics has demonstrated that the new components have a great deal of potential. More comprehensive testing and comparison of the results with existing ground water and geohydrological data is required, while some extensions to the new components need to be considered to ensure that the model can be considered applicable to a wide range of basin and climate types.

Key Words Hydrological models, ground water, surface water

INTRODUCTION

The focus of this paper is on a South African model that was developed for the purpose of water resource estimations within southern African. However, there is no reason why the model, the new ground water components and some of the observations made in this paper should not be applicable to other parts of the world. This is especially true of those regions that suffer some of the same problems of data scarcity and urgent requirements for regionalised water resource assessments as southern Africa.

While ground water represents a small proportion of the total utilised water resources of South Africa (between 10 and 15%), it is important locally and especially in the more arid regions of the country where surface water supplies are unreliable. It is also expected to become more important in the future as surface water supplies begin to reach the limit for sustainable development. The issue of sustainable development of water resources is entrenched in the South African National Water Act of 1998 which refers to the need to ensure that the requirements for basic human needs and the environment are met before potential users can be licensed to abstract water. The latter requirement is referred to as the ecological reserve and applies to both surface water bodies, as well as ground water. The procedures for assessing the reserve for rivers are reasonably well established (King et al., 2000; Hughes, 2000), however the same is not true for ground water. One of the complications with determining the ground water reserve is the lack of quantitative knowledge about the contribution that ground water makes to surface water and therefore the extent to which the two reserves are inter-linked.

Part of the problem lies in the way in which estimation methods (including simulation models) within the two hydrological disciplines have developed within South Africa. They have developed almost in isolation of each other and there have been few successful attempts to integrate them. Ground water hydrologists have focused on recharge estimation methodology (Bredenkamp, 1995) and the application of detailed finite element or finite difference ground water models for the estimation of borehole yields and the impacts of abstractions. Very few contributions in South Africa have focused on integrating ground and surface water estimation methods (Sami and Hughes, 1996) and the problem of ground water discharge to rivers. It has also been found to be difficult to apply both locally and internationally available surface-ground

water models due to the lack of detailed hydrogeological information in many parts of the country and the difficulties of calibrating such models without such information. A contributing factor is that the Pitman (Pitman, 1973) monthly rainfall-runoff model has become entrenched in South Africa as the preferred model for estimating the availability of surface water resources (Midgley et al., 1994). The current version of this model contains a 'ground water' outflow component, but it is not based on an explicit representation of the processes involved and the simulations are difficult to check against any available hydrogeological information or conceptual understanding.

Baseflow separation techniques using digital filtering of total streamflow data (Smakhtin, 2001, Hughes et al., 2003) have been used successfully in determinations of the ecological reserve for rivers to differentiate between high flow and baseflow streamflow components. However, these methods are not capable of identifying the source of the baseflow, which may not only consist of discharge from ground water but may also of throughflow output from downwardly percolating water in fractures above the water table. This process has been identified (although not documented) in areas of relatively steep topography where there is a lateral component to the alignment of fractures, such that percolating water can reach the surface and appear as springs before it reaches the ground water table. Many of the estimates of baseflow using separation methods are therefore greater than ground water hydrologists consider reasonable given their understanding and observations of recharge and water table behaviour. Baron et al. (1995) developed a national map of ground water harvest potential based on regionalised information about recharge and geohydrological properties. In the wetter and steeper parts of South Africa, baseflow estimates using separation techniques produce values which are frequently higher than 10 times the amount of ground water outflow that would be expected using the ground water harvest potential data.

The problem is therefore to determine methods of estimating recharge and ground water discharge time series from available data and to integrate them with a surface water estimation approach that would be considered acceptable by both surface and ground water hydrologists within South Africa. One of the logical starting points is therefore the widely accepted Pitman model. This paper summarises the structure of the Pitman model and the basis of simple recharge and discharge components that have been added in a way that minimises the changes to the overall model structure. The application of the new model is illustrated for two example basins and a number of observations are made about the success of the new components and additional model requirements that should make the model more widely applicable.

THE PITMAN MODEL

The Pitman model was first developed in 1973 (Pitman, 1973) and has become one of the most widely used monthly time-step rainfall-runoff models within Southern Africa. The basic form of the model has been preserved through all the subsequent versions that have been re-coded by the original author and others, but additional components and functionality have been added. The version that is referred to here is based upon modifications added during the application of the model for the first phase of the Southern African FRIEND programme (Hughes, 1997). The model has been incorporated into an integrated modelling framework (Hughes, 2002) that links spatial data with other data types (parameter tables and time series, for example) and includes a wide variety of data input, output and analysis routines as well as links to a variety of hydrological and water resource simulation models. The software package is being developed at the Institute for Water Research and is referred to as SPATSIM (Spatial and Time Series Information Modelling).

Figure 1 illustrates the structure of the Pitman model, while Table 1 provides a list of the parameters and brief explanations of their purpose. Additional compulsory data requirements

include basin area, a time series of basin average rainfall, seasonal distributions of evaporation (fractions), irrigation water demand (mm), other water demands (fraction) and monthly parameter distribution factors. Optional data requirements include optimisation ranges for parameters (ZMIN, ZMAX, ST, POW and FT), and time series of basin average potential evaporation, upstream inflow and transfer inflow. The SPATSIM version of the model represents a semi-distributed implementation of the model, whereby sub-basins are modelled with independent parameter sets and input time series. The details provided below are a summary of the main functions of the model and how changes in model parameters affect the simulation results.

Rainfall distribution function

The model operates over four iterations and the distribution of the total monthly rainfall is controlled by an s-curve function that depends on total rainfall and the RDF parameter. Lower values of RDF result in a more even distribution of rainfall, the effect being more pronounced for higher total rainfalls.

Interception function

This function is based on the interception parameter PI, which can vary seasonally and have values for two different vegetation types (typically, but not necessarily, natural vegetation and plantation forest). The parameter AFOR specifies the proportion of the basin under vegetation type 2. The depth of rainfall intercepted in any month is based on an empirical relationship between the relevant PI parameter and rainfall depth. Interception storage satisfies the evaporation demand at the potential rate.

Surface runoff function

In the original model surface runoff calculations are based on a symmetrical triangular distribution of basin absorption rates using parameters ZMIN and ZMAX to define the minimum and maximum absorption rates, respectively. For any given rainfall rate, the shaded area under the triangle effectively represents the relative proportion of the basin that is contributing to surface runoff. In the SPATSIM version of the model, ZMIN is allowed to vary seasonally and a third parameter (ZAVE) has been introduced to allow the triangle to become asymmetric. The parameter AI is used to represent the proportion of the basin that is impervious and in direct connection with the drainage system. All of the rainfall over this part of the basin generates surface runoff.

Soil moisture storage and runoff function

The proportion of rainfall that is not intercepted or that contributes to surface runoff, increments the moisture store and if the maximum value (ST) is exceeded, the balance becomes part of the runoff from the upper zone (Fig. 1). The ST parameter is referred to in the original model as soil moisture storage, while in fact this really represents all sub-surface storages in the basin (i.e. including ground water). Runoff from the moisture storage is controlled through a non-linear relationship between runoff and storage through the parameter POW (Fig. 2). At full storage, the runoff rate is $FT \text{ mm month}^{-1}$, of which $GW \text{ mm month}^{-1}$ is considered to be derived from outflow from ground water (or runoff from the lower zone) and is lagged separately (see later). At or below the parameter SL, no runoff occurs from the moisture store.

Evaporation from the moisture store

This function is controlled by the parameter R ($0 < R < 1$), as well as the current months potential evaporation value relative to the month with the highest potential evaporation. A low value for R implies 'more effective' evaporation loss and allows evaporation to occur even at quite low levels of the moisture store. A high value of R suggests that evaporation losses cease at relatively high moisture storage levels for months with relatively low evaporative demand. A low R therefore implies deeper rooting of vegetation. To allow for two different rates of evaporative loss for the different vegetation types, parameter FF is used and simply scales the potential evaporation rate for the area of the basin covered by the second vegetation type.

Runoff delays and lags

The runoff from the upper and lower zones are lagged separately using parameters TL and GL , which refer to the lag parameters in the Muskingham routing equation with the weighting factor set to zero to represent reservoir-type storage attenuation.

Functions to represent artificial modifications to the hydrology

The first of these is the small farm dam routine, which allows runoff generated in part of the basin ($DAREA$) to be intercepted by the available storage in any number of dams grouped together and represented by the storage given by the parameter $MDAM$. Evaporation losses from the dams surface are accounted for through a non-linear area-volume relationship and abstractions from the dam using the $IRRIG$ parameter and the monthly irrigation requirements. These dams only influence runoff generated from within the specific sub-basin of the distribution system and cannot be filled from water generated in upstream catchments. The second artificial influence is through direct pumping of irrigation water from the main channel. This function operates on water available at the sub-basin outlet (i.e. including upstream runoff) and is controlled by the monthly distribution of gross irrigation demand, the area of irrigation parameter ($AIRR$) and the effective rainfall fraction (used to reduce gross demand to net demand after rainfall). A proportion of the irrigation abstraction can be returned to the river as return flow (IWR). The final artificial modification is through the annual value representing non-irrigation demand ($RUSE$) and the monthly distribution values. This water is also taken from the main channel at the sub-basin outlet. Figure 1 illustrates that an optional reservoir model can be configured (with an additional set of parameters values) at each sub-basin outlet.

THE NEW COMPONENTS

Recharge

The basis of the recharge component is that the surface characteristics can be represented by a single storage given the possibility that direct recharge can occur where there are bare rock areas. A parameter is required to represent the storage below which no recharge is expected to occur (soil water storage up to field capacity). The depth of recharge can then be estimated as a non-linear relationship between recharge depth and the ratio of current storage to the maximum storage.

The Pitman model already simulates soil moisture storage, while the SL parameter is normally set to zero and plays no real role in the current version of the model. The proposed restructuring therefore makes use of SL as the soil moisture threshold below which recharge does not occur, while its effect on soil moisture runoff generation is removed. Parameter GW is

redefined as the maximum amount of recharge (at a moisture status equal to ST) and a new parameter GPOW introduced to determine the form of the relationship between recharge and current storage S (Fig. 2).

$$RE = GW \{(S - SL) / (ST - SL)\}^{GPOW} \dots\dots\dots \text{Eq. 1}$$

Ground water discharge

The basis of this component is to reduce the complexity of the spatial geometry of the basin to a simpler geometrical arrangement. The starting point is to assume that the basin is square and that the channels can be represented by parallel lines, separated by drainage slopes. The drainage slopes consist of the two areas between the edges of the square and the outermost 'channels', plus two between each 'channel' line (Fig. 3). Drainage is initially assumed to be only in 1-dimension for simplicity. The determination of the number, length and width of the drainage slopes can therefore be based on the basin area and the effective drainage density. The channels included in the effective drainage density are those that can be considered to be the main recipients of ground water discharge and could exclude smaller tributary channels that are only actively flowing during storm events.

The number of channel lines can be calculated from:

$$\text{Total channel length} = \text{Drainage density} * \text{Area} \dots\dots\dots \text{Eq. 2}$$

From Fig. 3:

$$\text{Total channel length} = \text{No. drainage slopes} * \text{SQRT}(\text{Area}) / 2 \dots\dots\dots \text{Eq. 3}$$

Therefore:

$$\text{No. drainage slopes} = \text{Integer even value of } \{\text{Drainage density} * \text{SQRT}(\text{Area}) * 2\} \dots\dots\dots \text{Eq. 4}$$

$$\text{Width of drainage slope} = \text{SQRT}(\text{Area}) / \text{No. of drainage slopes} \dots\dots\dots \text{Eq. 5}$$

Figure 4 illustrates the 3-dimensional situation for a single drainage slope element and the volume of the 'wedge' of ground water stored under that drainage slope (assuming that the lower boundary is the channel at the bottom of the slope) can be calculated as:

$$\text{Volume} = (\text{Drainage width})^2 * \text{Gradient} * \text{Drainage length} / 2 \dots\dots\dots \text{Eq. 6}$$

While the volume of stored water will be wedge volume * storativity. Outflows from this wedge, within a single slope element can be calculated by:

$$\text{Discharge} = \text{Transmissivity} * \text{Gradient} * \text{Time step} * \text{Channel length} \dots\dots\dots \text{Eq. 7}$$

While the proposed geometric representation of ground water flow towards a river channel is very simplistic and ignores many of the realities of ground water movement, it is nevertheless useful as most of the calculations are simple geometric equations. The model formulation consists of adding the recharge to the volume of stored ground water, re-calculating the slope, calculating the outflows and updating the volume of stored ground water for the next time step. It should be noted that the initial gradient value is not particularly important as the other parameters determine what the pattern of gradient changes will eventually be. While it may not

be the drainage gradient that changes as ground water contributions to surface flow vary (it could be contributing area or other factors), nevertheless the effect of changing the gradient has the desired effects:

- More recharge, more outflow in the future.
- If drainage is greater than recharge the outflow will gradually decline.
- Lower drainage density, less outflow.

APPLICATION EXAMPLES

The objectives of the initial model tests were:

- To ensure that the model (as coded within the SPATSIM package) generates stable and consistent results.
- To calibrate the two versions of the model and compare the calibration effort required, as well as the results.
- To ensure that the calibrations are achieved with realistic values for the new parameters and that the resulting recharge rates are realistic.

Two basins have been included in these initial tests. The first is a 581 km² basin (the Buffelspruit River, X1H016 at 25°56'50"S 30°34'07"S, a tributary of the Komati River) located on the eastern escarpment of Mpumalanga province in South Africa. The terrain is undulating and the soils are moderate to deep sandy loams developed on quartzites and shales in the upper parts of the basin and on metamorphosed migmatite and gneiss in the lower areas. There is also a narrow band of dolomites in the middle of the basin. The mean annual rainfall is some 870mm and the mean annual potential evaporation about 1400mm. There are over 30 years of observed flow data with very few gaps and while there are known to be some small farm dams and a limited amount of irrigation water usage, these are not thought to be substantial and have been ignored in the simulations. The rainfall input to the models has been based on the regional rainfall data provided in the WR90 reports (Midgely et al., 1993).

The second basin is the Cuito River (15 193 km²), situated in south eastern Angola and a tributary of the Okavango River. The terrain is hilly and the underlying geology consists of Kalahari sands, which are known to be relatively permeable and give rise to high baseflow rainfall-runoff responses. The mean annual rainfall is approximately 1130 mm, while the mean annual potential evaporation is some 2100 mm. There are only 9 years of available observed flow data and some extended periods of missing data. The basin average rainfall inputs have been estimated as part of the WEERD (Water and Ecosystem Resources in Regional Development – an EU supported multi-disciplinary study on the Okavango basin) programme based on a limited number of raingauges in the vicinity of the basin.

In the case of the South African basin the procedure was to calibrate the original Pitman model first and to retain the values of most of the parameters that are shared between the versions during the calibration of the revised ground water model. The parameters that were allowed to change were FT, GW, ST and GL. A calibration for the original model version for the Cuito basin already existed and the new model was calibrated independently with all parameters being allowed to change. Table 3 lists the calibrated parameter values, while Table 4 lists the statistics of correspondence between observed and simulated flows (R^2 = Coefficient of Determination, CE = Coefficient of Efficiency). Fig. 5 and 6 provide graphical comparisons of observed and simulated flows for both models.

Neither of the simulations for X1H016 are particularly good and this may be a reflection of the quality of the rainfall input data. However, it is noteworthy that both models generate similar results, both in terms of the statistics (Table 4) and the pattern of simulated flows (Fig.

5). The mean annual recharge simulated by the revised Pitman model is 42 mm or 4.8% of mean annual rainfall (28% of mean annual total runoff), which is within the range of recharge values expected for this part of South Africa (Bredenkamp et al., 1995). This estimated recharge figure also agrees reasonably well with the values given in Baron et al. (1998) for the ground water harvest potential in this area (31% of mean annual runoff), which was estimated on the basis of available hydrogeological information, as well as data provided in Vegter(1995). The application of a baseflow separation approach using the daily or monthly streamflow time series and a digital filtering approach (Smakhtin, 2001; Hughes et al., 2003) suggests that the total baseflow response of this basin could be up to 50%, almost double the simulated ground water component. This illustrates the difficulty of relying upon numerical baseflow separation procedures to infer the source, or hydrological process that generates the baseflow. The revised model was found to be somewhat more difficult to calibrate due to the larger number of parameters. However, in most situations the likely range of values for drainage density, storativity and transmissivity would be known, which limits the calibration exercise mainly to the three parameters (SL, GW and GPOW) affecting recharge. GL (ground water lag time) becomes redundant in the new model as other parameters affect the degree of attenuation of ground water discharge relative to rainfall.

A different calibration approach was adopted for the Cuito basin, largely because the surface runoff, evaporation and lag time calibrated parameter values of the original model did not appear to be appropriate for the new model. This is partly due to the fact that the lag time for a large part of the generated runoff in the original model (8 months) was very high, while it was fixed at zero in the new model. Recharge equals approximately 14% of rainfall, while the simulated ground water contribution to total flow is some 74%. Unlike the previous basin this figure is close to the 80% baseflow contribution given by a digital filtering approach.

The results of the new model are a small improvement on the results from the original model (Table 4 and Fig. 6). However, from a perspective of the way in which the two models represent the actual processes involved in the runoff generation process, the new model and its parameter set (Table 3) are considered to be a great improvement. Unfortunately, at present, this conclusion remains speculative as there is insufficient field information about the basin to confirm any conceptual ideas about how runoff generation processes operate.

DISCUSSION AND CONCLUSIONS

While it is not suggested that the new components are a totally realistic representation of ground water flow in a drainage basin, they have the right effects and the majority of the parameter values of the model should be quantifiable from existing information. The GL parameter is no longer required as the transmissivity and drainage density parameters largely control the lag and attenuation of ground water discharge for a given pattern of recharge and storativity. The initial drainage slope is also largely superfluous as the balance of inflow and outflow determines the patterns of slope variation and the model seems to 'warm up' from a range of starting values after about 10 to 25 months. The new components are conceptually consistent with the original model in that they are neither more, nor less, complex. In many ways this is an important consideration when adding new components to an existing model. There is little purpose in adding more complex components to a relatively simple model or adding really simple components to a complex model. Both will result in a lack of balance between components and add to the difficulties of interpreting model results, particularly when undertaking regional calibrations across a wide range of basin and climate characteristics.

It could be argued that the ground water parameters will not always be simple to quantify. However, the two example basins illustrate that even with only a limited *a priori* understanding of the likely geohydrological conditions, sensible parameter values have been

established after calibration. The new parameters therefore have at least equal, if not more, physical meaning and interpretation than the other parameters of the Pitman model. This should make it a relatively straightforward task to use existing geohydrological information at a national scale to develop regionalised parameter value data sets. Initial estimates of the ground water parameters could then be checked and revised through a limited programme of model calibration and validation for key basins within the country.

It is concluded that the initial developments of the ground water components have been successful and are worth pursuing through further calibration and validation tests with the ultimate aim being to replace the existing Pitman model as the recommended model for use in water resource evaluations in South Africa as well as many other countries of southern Africa.

There are a number of situations that are not accommodated for in the model. Specifically these relate to ground water abstractions, evaporative losses of ground water discharge from riparian areas, ground water discharge to aquifer compartments in adjacent sub-basins and situations where the ground water level is below the river level for all or part of the time (i.e. no discharge).

Extensions to the model

If it is assumed that abstractions from ground water represent a reduction in volume and therefore a reduction in gradient, then simple abstractions can also be accounted for in exactly the same way as outflow and recharge. A separate estimation equation will be needed for abstractions from riparian areas because these are expected to have a greater impact than abstractions from areas remote from the channels.

Losses at the channel margins (through evaporation and transpiration from riparian vegetation) can be accounted for as well through a simple reduction (based on potential evaporation rates and vegetation type and density) of the outflow volume. It should also be possible to add a simple function to represent losses from storage due to sub-surface outflow to a downstream basin area (i.e. a second slope dimension in addition to the drainage slope). This will be an important feature in a semi-distributed model where several linked sub-basins are modelled together.

The model has been conceptualised for situations where there is expected to be a more or less permanent contribution of ground water to streamflow and there are still some issues to be resolved before the model can be used in situations where the ground water fluctuates over time at levels above and below the streambed. If the model is to be applicable to a wide range of basins throughout southern Africa, it will also be necessary to consider situations where the ground water level rarely (if ever) reaches above the level of streambeds.

All of these extensions will be added to the model before further extensive testing on a range of basins will be undertaken.

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Table 1 Pitman model parameters.

Parameter	Units	Description
RDF		Rainfall distribution factor. Controls the distribution of total monthly rainfall over four model iterations.
AI	Fract.	Impervious fraction of sub-basin.
PI1 and PI2	mm	Interception storage for two vegetation types.
AFOR	%	% area of sub-basin under vegetation type 2.
FF		Ratio of potential evaporation rate for veg2 relative to Veg1.
PEVAP	mm	Annual basin potential evaporation
ZMIN	mm mnth ⁻¹	Minimum basin absorption rate.
ZAVE	mm mnth ⁻¹	Mean basin absorption rate.
ZMAX	mm mnth ⁻¹	Maximum basin absorption rate.
ST	mm	Maximum moisture storage capacity.
SL	mm	Minimum moisture storage below which no runoff occurs.
POW		Power of the moisture storage-runoff equation.
FT	mm mnth ⁻¹	Runoff from moisture storage at full capacity (ST).
GW	mm mnth ⁻¹	Maximum runoff from ground water.
R		Evaporation-moisture storage relationship parameter.
TL, GL	months	Lag of runoff (surface and ground water, respectively).
AIRR	km ²	Irrigation area.
IWR	Fract.	Irrigation water return flow fraction.
EFFECT	Fract.	Effective rainfall fraction.
RUSE	MI y ⁻¹	Non-irrigation demand from the river.
MDAM	MI	Small dam storage capacity.
DAREA	%	% sub-basin above dams.
A, B		Parameters in non-linear dam area-volume relationship
IRRIG	km ²	Irrigation area from small dams

Table 2 Redefined or new parameters in the revised Pitman model

Parameter	Units	Description
SL	mm	Redfined - soil moisture below which there is no recharge
GW	mm	Redefined – Max. recharge depth at maximum moisture capacity
GPOW		New - Power of the moisture storage-recharge equation.
DR	%	New – Direct recharge zone as a % of total catchment area
DD	Km km ⁻²	New – Effective drainage density
T	M ² d ⁻¹	New – Transmissivity
S		New – Storativity
Slope		New – Initial ground water drainage slope

Table 3 Calibrated model parameter values

Parameter	Cuito		X1H016	
	Original	GW Model	Original	GW Model
Rain Distribution Factor	1.2	1.2	1.2	1.2
Proportion of impervious area AI	0	0	0	0
Intercept cap.(Veg1) PI1	1.5	1.5	1.5	1.5
Intercept cap.(Veg2) PI1	4.0	4.0	4.0	4.0
% Area of Veg2 AFOR	60	60	0	0
Veg2/Veg1 Pot. Evap. Ratio FF	1.1	1.1	1.4	1.4
Min. abs.rate (mm/mth) ZMIN	80	50	25	25
Mean abs.rate (mm/mth) ZAVE	600	1000	320	320
Maximum abs.rate (mm/mth) ZMAX	900	1400	520	520
Maximum storage capacity ST (mm)	1000	1100	400	400
No runoff below storage SL (mm)	0	200	0	100
Power : storage-runoff curve POW	1.5	3.2	2.3	2.3
Runoff rate at ST (mm/mth) FT	38.0	15.0	22.0	10.0
Max. groundwater flow/recharge (mm/mth) GW	38.0	40.0	8.0	20.0
Evaporation-storage coefficient R	0.8	1.0	0.5	0.5
Surface runoff time lag (mnths) TL	1.0	0.25	0.25	0.25
Groundwater time lag (months) GL	8.0	0.0	2.5	0.0
Power Storage-recharge curve GPOW	N/A	1.5	N/A	2.0
Drainage density	N/A	0.4	N/A	0.5
Transmissivity (m ² d ⁻¹)	N/A	10.0	N/A	8.0
Storativity	N/A	0.01	N/A	0.002
Initial GW drainage slope	N/A	0.03	N/A	0.02

Table 4 Simulation results

Basin – Model	Normal		Ln Values		Mean Monthly % Error	
	R ²	CE	R ²	CE	Normal	Ln
Cuito - Original	0.708	0.626	0.727	0.713	-1.3	-0.2
Cuito – GW Model	0.743	0.734	0.751	0.749	-1.2	-0.1
X1H016 – Original	0.434	0.200	0.674	0.660	-0.1	0.0
X1H016 – GW Model	0.446	0.205	0.700	0.672	1.8	-0.2

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- Fig. 5 Comparison of monthly observed and simulated flows for basin X1H016 for 8 years.
- Fig. 6 Comparison of monthly observed and simulated flows for the Cuito basin for 6 years.

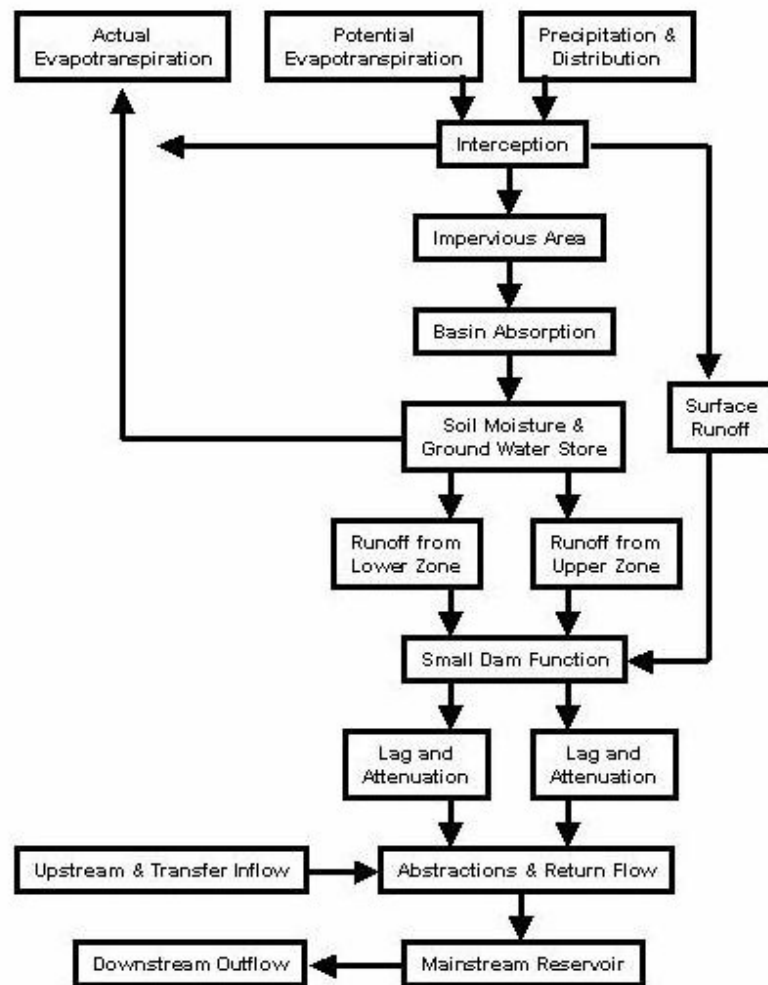


Figure 1 Flow diagram representation of the original Pitman model.

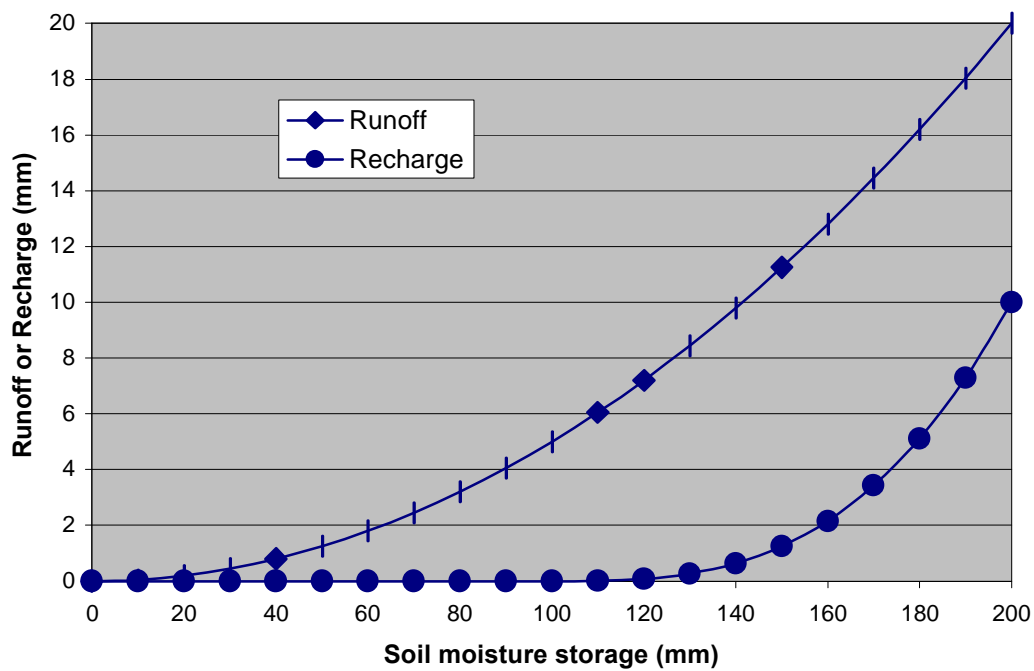


Figure 2 Illustration of the original soil moisture runoff function (with parameter ST=200, SL=0, FT=20 and POW=2) and the additional recharge-moisture state relationship with parameter SL=100, GW=10 and GPOW=3.

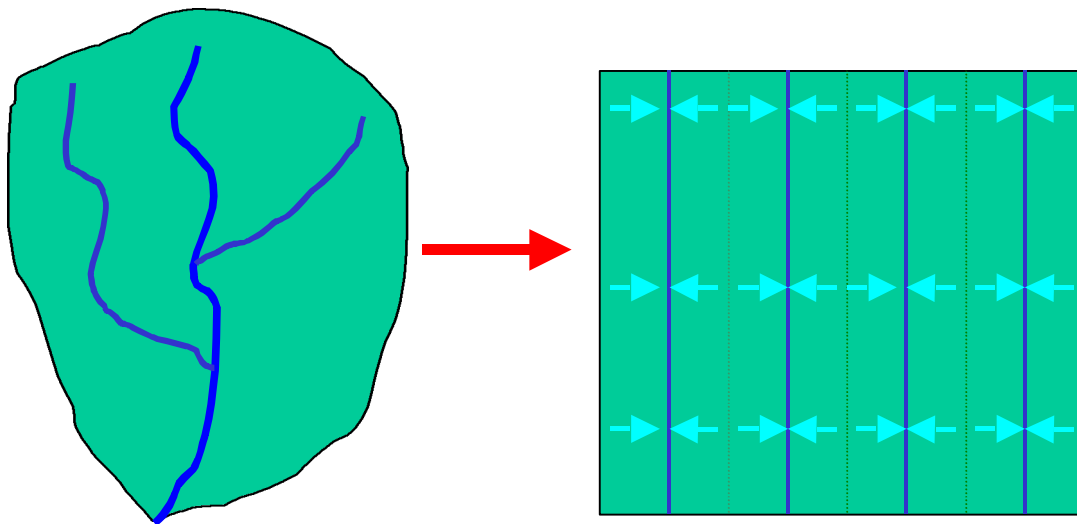


Figure 3 Conceptual simplification of drainage in a basin for a drainage density of $4/\text{SQRT}(\text{Area})$ (solid lines are channels, dashed lines are drainage divides and arrows show drainage directions). There are 8 drainage slopes

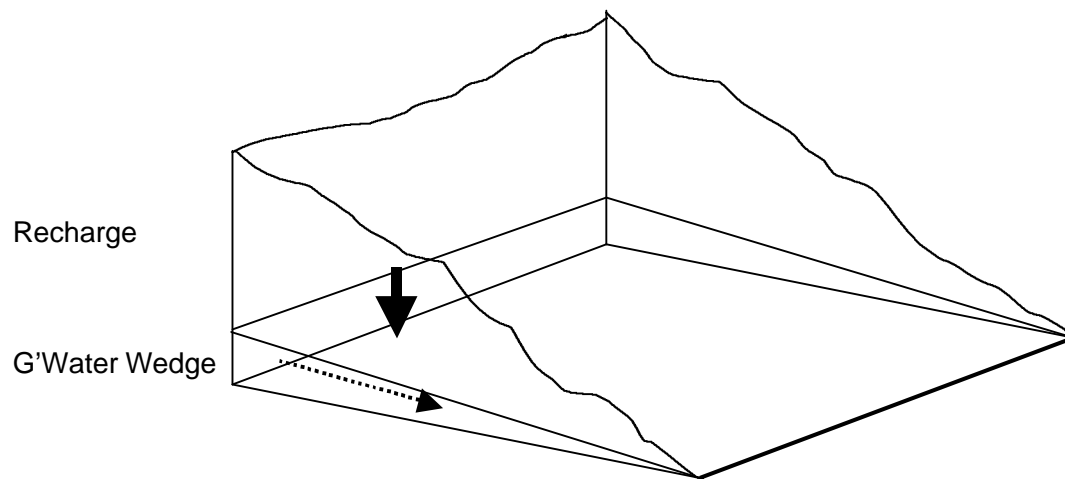


Figure 4 Illustration of a single drainage slope element. The thick arrow indicates recharge water from the surface to the ground water 'wedge', the thin arrow indicates the direction of drainage. The 'wedge' represents the part of the ground water body that is above the conceptual river channel and can contribute to discharge.

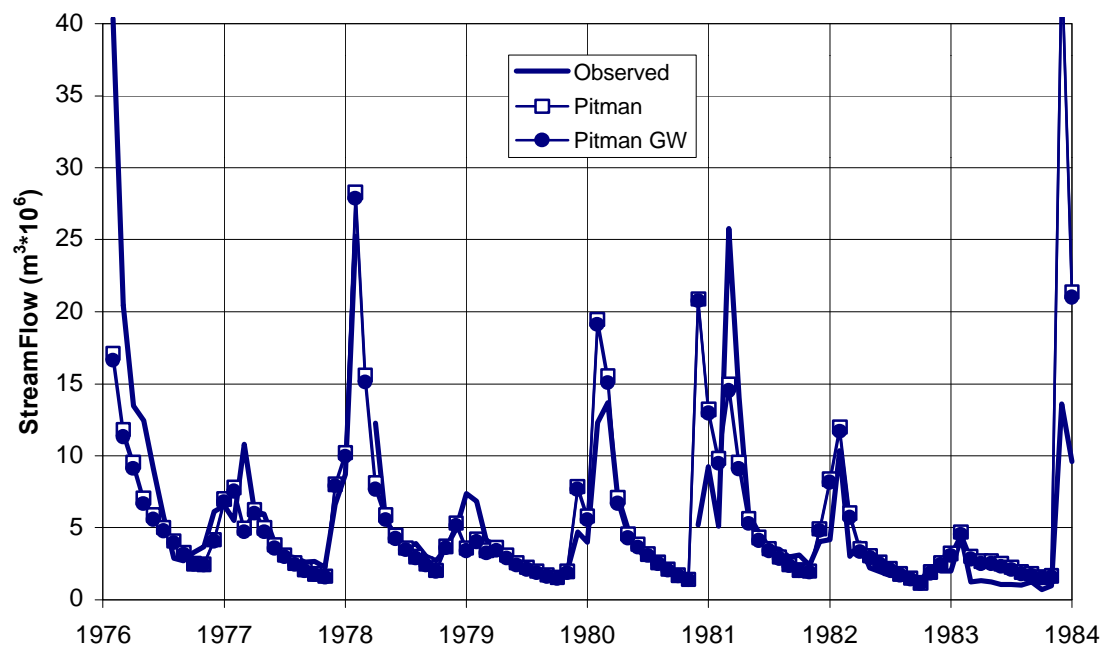


Figure 5 Comparison of monthly observed and simulated flows for basin X1H016 for 8 years.

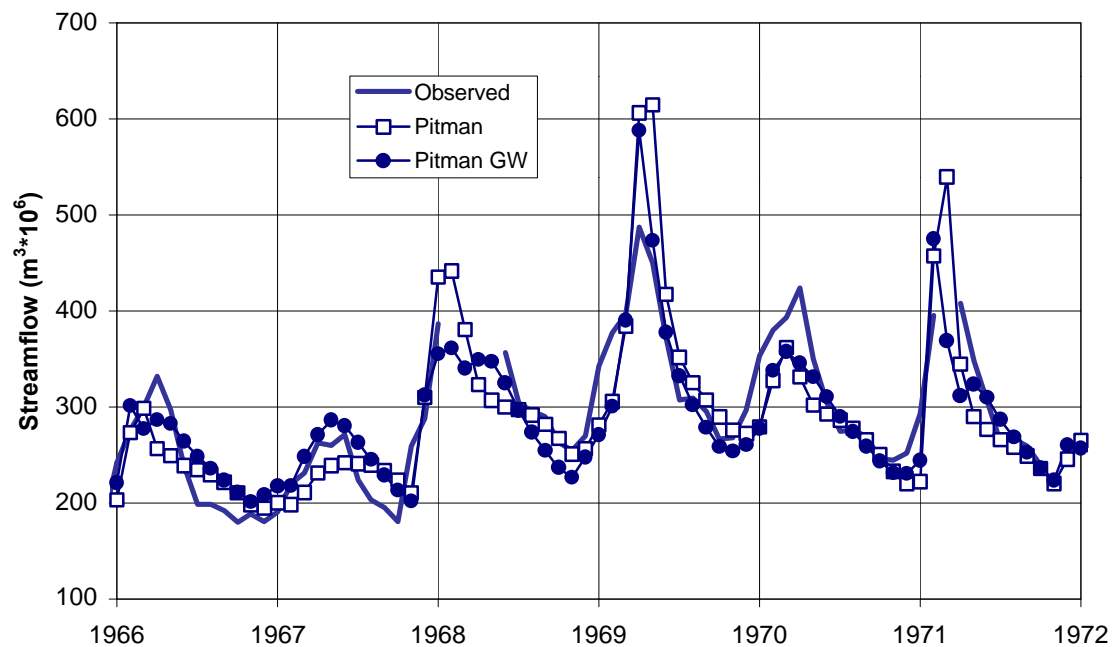


Figure 6 Comparison of monthly observed and simulated flows for the Cuito basin for 6 years.