Quantification of the Groundwater Contribution to Baseflow

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Since promulgation of the National Water Act and the need to set aside water for aquatic ecosystems, it has emerged that surface - groundwater interaction is poorly understood and even more difficult to quantify. A research project was consequently undertaken to develop a prototype tool to:

- identify rivers in South Africa dependent on groundwater for sustaining baseflow, and
- develop methods and models to quantify the groundwater contribution to baseflow.

A prototype model was developed in a modular fashion to accommodate inclusion of results of parallel research being undertaken by the Department of Water Affairs and Forestry and the Water Research Commission. Using data sets generated during the Groundwater Assessment Phase II project, the Pitman model was modified to facilitate the quantification of the groundwater contribution to baseflow. This entailed consideration of recharge, groundwater discharge to streamflow and abstraction.

The revised Pitman model was then included in the SPATSIM software and tested in a number of quaternary catchments across South Africa. The model was calibrated against existing WR90 simulated monthly time series data. In general terms, the revised algorithms appeared to generate results that were intuitively realistic as well as replicate hydrographs produced using the original Pitman model while taking into account groundwater factors. Some problems were encountered in dolomitic catchments, but these are thought to be the result of the modeling approach used by WR90 and not the result of problems with the modified Pitman model.

Based on the calibration and testing of the revised Pitman model in 17 quaternary catchments, guidelines were developed for estimating the groundwater parameters used in the model. Incorporation of the modified Pitman model into the SPATSIM software has provided hydrologists with a useful tool to quantify surface - groundwater interaction at a catchment scale. Proper training in the use of the software is required yield reliable results.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND NOTATIONS USED

SYMBOL	DESCRIPTION
AREA_M2	Area in m^2
CATNUM	Quaternary catchment no as per WR90
CMAP	CMAP from WR90
DDENS	Drainage density
DWAF	Department of Water Affairs and Forestry
EBFI	Estimated baseflow index
GIS	Geographical Information Systems
GPOW	Power : Storage-Recharge curve
GRAII	Groundwater Resources Assessment Phase Two Project
GWA_upper	GW Abstraction (Upper slopes-Ml y^{-1})
GWA lower	GW Abstraction (Lower slopes-Ml y^{-1})
GW	Max. Recharge rate (mm/month)
MAP_MM3	MAP in Mm^3 calculated from CMAP
MAP	mean annual precipitation
MAR	MAR from WR90
MAR	mean annual runoff
MAX_KS	Maximum calculated recharge percentage from GRAII - GIS calibrated against Karim Sami's output
MAX_RDM	Maximum calculated recharge percentage from GRAII - GIS calibrated against output from RDM office
MAX_RDM_MM3	Maximum calculated recharge volume from GRAII - GIS calibrated against output from RDM office
MAX_MM3_KS	Maximum calculated recharge volume from GRAII - GIS calibrated against Karim Sami's output
MEAN_KS	Mean calculated recharge percentage from GRAII - GIS calibrated against Karim Sami's output
MEAN_MM3_KS	Mean calculated recharge volume from GRAII - GIS calibrated against Karim Sami's output
MEAN_RDM	Mean calculated recharge percentage from GRAII - GIS calibrated against output from RDM office
MEAN_RDM_MM3	Mean calculated recharge volume from GRAII - GIS calibrated against output from RDM office
MEAN_SLP_P	Mean slope per catchment (percentage) from 1x1 km grid based on DWAF DTM
MEAN_SSATI	Mean SSATI per catchment from Vegter's SSATI dataset
MEAN_STHK	Mean saturated thickness from Vegter 1995. The mean thickness of that part of the saturated zone which contains the bulk of the most readily accessible groundwater was taken on average to be half the optimal drilling depth below the water level.
MEAN_TRANS	Mean transmissivity per catchment - Transmissivity (m^2/day) derived from borehole yields (from NGDB & Paul du Plessis)
MED_SSATI	Median SSATI per catchment from Vegter's SSATI dataset
MED_STHK	Median saturated thickness per catchment from Vegter 1995
MIN_KS	Minimum calculated recharge percentage from GRAII - GIS calibrated against Karim Sami's output

MIN_MM3_KS	Minimum calculated recharge volume from GRAII - GIS calibrated against Karim Sami's output
MIN_RDM	Minimum calculated recharge percentage from GRAII - GIS calibrated against output from RDM office
MIN_RDM_MM3	Minimum calculated recharge volume from GRAII - GIS calibrated against output from RDM office
RECHP	Mean calculated recharge percentage from GRAII - output from GIS calibrated layer
RECH_MM3	Mean calculated recharge volume from GRAII - output from GIS calibrated layer
RECH_MM_feb05	Mean calculated recharge depth from GRAII - output from GIS calibrated layer
RECHMIN_MM3	Minimum calculated recharge volume from GRAII - output from GIS calibrated layer
RECHMAX_MM3	Maximum calculated recharge volume from GRAII - output from GIS calibrated layer
RECHMIN	Minimum calculated recharge percentage from GRAII - output from GIS calibrated layer
RECHMAX	Maximum calculated recharge percentage from GRAII - output from GIS calibrated layer
RECHRNG	Range of calculated recharge percentages from GRAII - output from GIS calibrated layer
RG	Regional GW drainage slope
RSF	Riparian Strip Factor (% slope width)
RWL	Rest water level (m below surface)
S	Storativity
SL	No recharge below storage (mm)
SLOPE	Mean slope per catchment (degrees) calculated from 1x1km grid based on DWAF DTM
T	Transmissivity (m^2/day)
TLGMax	Maximum Channel Loss (mm)
TOTAL_USE	Total GW use Mm^3 from GRAII
USEOFRECH	Use as a percentage of calculated recharge (uncalibrated GIS method output)
WRC	Water Research Commission
WR90	Surface Water Resources of South Africa 1990

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Input by Mr Karim Sami during modification of the Pitman model is also acknowledged.

1 INTRODUCTION

1.1 Rationale for Research

Promulgation of the National Water Act (Act 36 of 1998) requires water be set aside for basic human needs and aquatic ecosystems before allocation to other potential users (DWAF, 1999, 199a). Through research and development undertaken to develop tools and methods required to quantify the Ecological Reserve, it has emerged surface – groundwater interaction is poorly understood, and even more difficult to quantify (Parsons, 2004). It is now apparent baseflow (as determined by baseflow separation techniques – see Smakhtin, 2001 and Hughes *et al.*, 2003) is not equivalent to groundwater discharged into some rivers and interflow plays a contributing role to low flows in rivers.

By implication, this means the role of groundwater in sustaining the Reserve (particularly during low flow periods) varies significantly across South Africa. In some instances, the role of groundwater will be considerable and any Reserve determination will require a major groundwater component. In other instances, groundwater's role will be very small, with a concomitantly small geohydrological input into the study.

The allocation of human and financial resources will be optimized if tools are available to assess and quantify the role of groundwater in sustaining the Reserve. These tools will permit the RDM office to prioritise their groundwater-related efforts.

1.2 Objectives

The overall objectives of the project was to develop a prototype tool to identify rivers in South Africa dependant on groundwater for sustaining baseflow and demonstrate that the developed methods can be used to quantify the contribution. Specific goals included:

- Using currently available national scale data, prepare a set of GIS-based maps indicating the degree of groundwater contribution to baseflow.
- Develop methods and models to quantify the groundwater contribution to baseflow, including modification of the Pitman model.
- Include the modeling routines into the SPATSIM framework.
- Test the developed tool in at least 10 catchments.
- Develop a set of management tools to ensure the groundwater contribution to baseflow is not impacted by abstraction.
- Document the results of the research and prepare a users manual

1.3 Methodology

The prototype model was developed in a modular fashion to accommodate inclusion of results of parallel research being undertaken by DWAF and the WRC. Data generated during the Groundwater Resource Assessment Phase II (GRAII) project, for example, was obtained and used to prepare GIS coverages required for the project (Conrad, 2005).

Using these data coverages, the Pitman model was modified to facilitate the quantification of the groundwater contribution to baseflow (Hughes, 2004; Hughes and Parsons, 2005). Care was taken to ensure as few additional parameters as possible were added to the model. The modified Pitman model was then incorporated into the SPATSIM framework to increase its capabilities as a tool for Reserve determinations.

Independent to the WRC project, DWAF included a surface groundwater interaction component in the GRAII project (DWAF, 2003). Interaction between the two project teams allowed for discussion and an exchange of ideas.

Once the modified Pitman model had been developed, the model was tested in about 10 catchments. As no quantified information are available regarding the groundwater contribution to baseflow, the results of the model were assessed based on an intuitive understanding of conditions in those catchments.

This report documents the findings of the research and provides guidance on setting those parameters in the modified Pitman model specific to groundwater.

2 GROUNDWATER DATA SETS

Data required by the Pitman model is included in the surface water resources of South Africa (WR90) data set (Midgley *et al.*, 1994), but similar data sets for groundwater were not available. Initial research into revising the Pitman model to accommodate the groundwater contribution to baseflow suggested national scale information pertaining to recharge, transmissivity, storativity and the hydraulic gradient were required. It was also considered prudent to identify areas in which groundwater is likely to contribute to baseflow.

While it is widely accepted that groundwater contributes to baseflow, the quantification of the contribution is difficult. A number of baseflow separation techniques using digital filters can be used to estimate baseflow (Smakhtin, 2001; Hughes *et al.*, 2003). However, these techniques are not capable of identifying the source of the baseflow. Baseflow could be derived from discharge from groundwater and / or downward percolating water in fractures above the water table.

As rivers in the drier western part of South Africa have no or very little baseflow, it was assumed a baseflow index could be used to identify those areas in which groundwater contributes to baseflow (Figure 1). The probability of groundwater contributing to baseflow is low when the baseflow index is less than 0.05. Similarly, the probability of groundwater contributing to baseflow is considered high when the baseflow index is greater than 0.25.

One of the deliverables of the GRAII project was a national scale recharge map. A first approximation of recharge was obtained using the chloride mass balance approach (Conrad, 2005). This was then calibrated using site-specific estimates of recharge presented in the literature (Figure 2). The national scale assessment of recharge presented a mean recharge value (expressed as a percentage of mean annual precipitation), as well as lower and upper values.

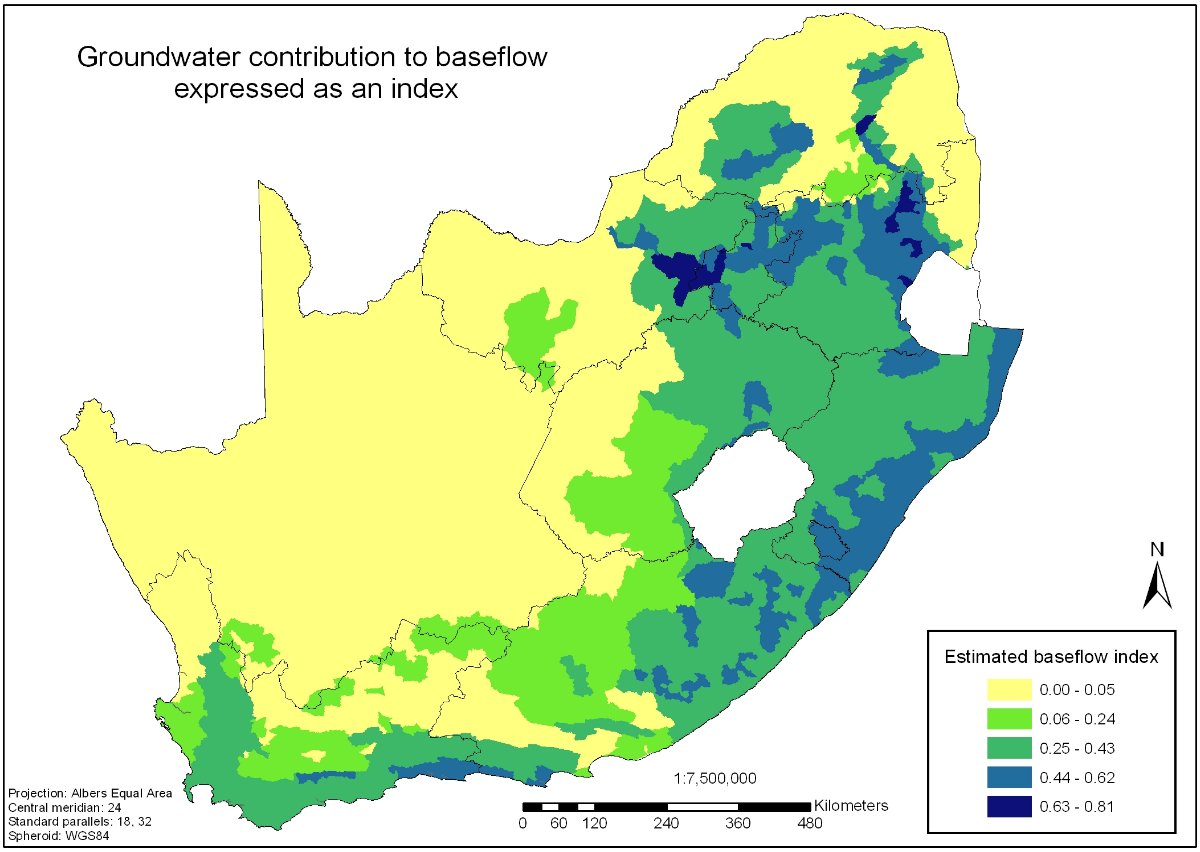

Figure 1: **Baseflow index of quaternary catchments in South Africa.**

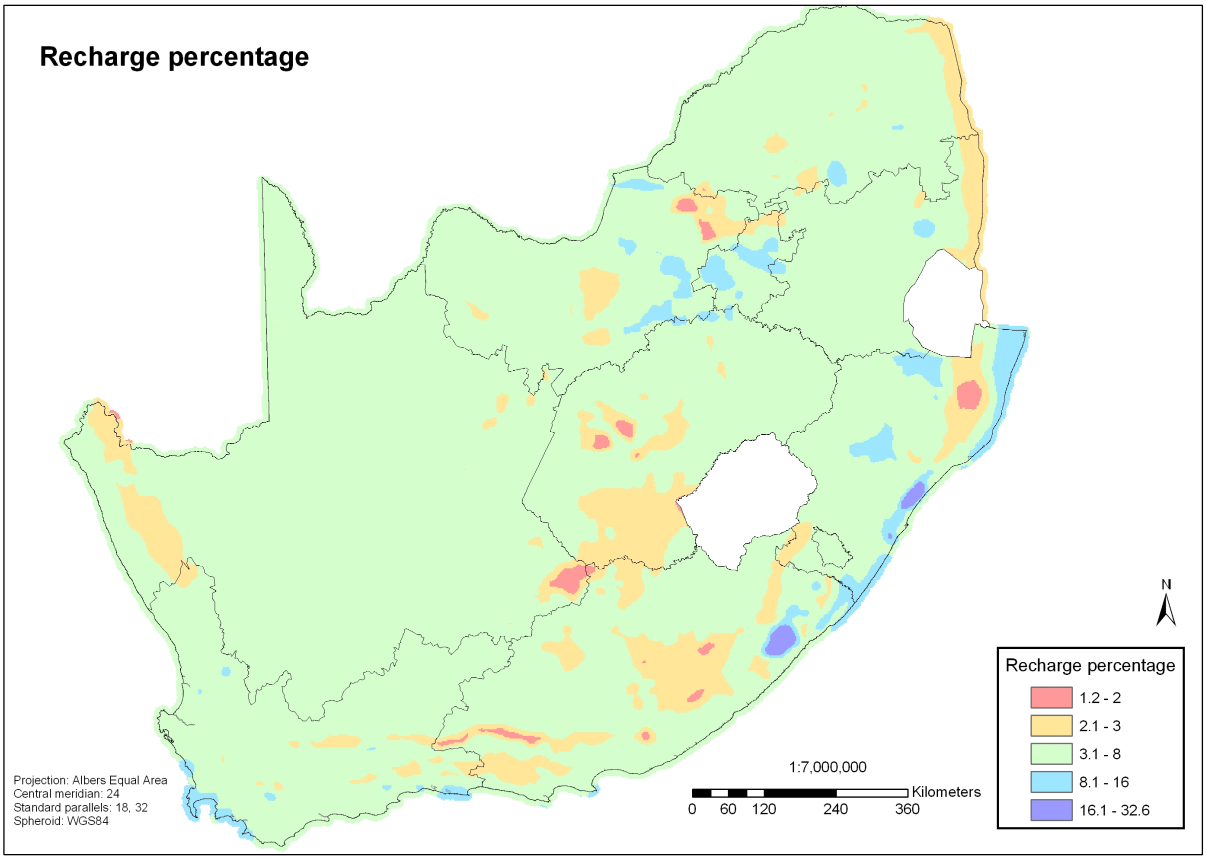

Figure 2: **Recharge map of South Africa, expressed as a percentage of mean annual precipitation.**

Other national scale data sets to be generated for the project were a transmissivity map and a surface slope map, while the storativity map prepared by Vegter (1995) was adopted. It is exceptionally difficult to present transmissivity at a national scale. This is because of the fractured and weathered nature of aquifers in South Africa, and their variability over short distances. However, transmissivity was approximated using the following relationship:

$$T = 10\,q \tag{1}$$

where T = transmissivity (m^2/d) and q = borehole yield (L/s)

Borehole yield data was obtained from the NGDB and an average yield computed for 1 km by 1 km grids. The value was then multiplied by 10 to approximated transmissivity. In the absence of site-specific data, topographical slope can be used to approximate hydraulic gradient. It was hence considered prudent to determine the slope of 1 km by 1 km cells across the country using a 20 m Digital Elevation Model.

3 MODIFICATIONS TO THE PITMAN MODEL

3.1 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 in subsequent versions recoded by the original author and others, but additional components and functionality have been added. Figure 3 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, irrigation water demand, and other water demand and monthly parameter distribution factors. Optional data requirements include time series of basin average potential evaporation, upstream inflow and transferred inflow. The structure and functioning of the model is described by Hughes (2004).

Earlier versions of the Pitman model contained a “groundwater” component, but it was not based on an explicit representation of the processes involved. Further, simulations are difficult to check against any available geohydrological information or conceptual understanding. Baseflow separation techniques using digital filtering of total streamflow data have been used successfully to differentiate between high flows and baseflow stream flow components. In this context “baseflow” is considered as the low amplitude, high frequency component of the total flow hydrograph; without reference to the source of the water. These methods are therefore not capable of identifying the source of the baseflow, which may consist not only of discharge from groundwater but also of interflow (also referred to as throughflow) from downward percolating water in fractures above the water table. Many of the estimates of baseflow using numerical separation methods are therefore greater than ground water hydrologists consider reasonable given the understanding and observations of recharge and water table behaviour. In the wetter and steep parts of South Africa, baseflow estimates using numerical separation techniques produce values that are frequently higher than 10 times the amount of groundwater outflows that would be expected.

The version of the Pitman model modified during the research programme is that integrated into the SPATSIM software package (Hughes, 2002). This software package links spatial data with other types of data (parameter tables and time series, for example) and includes a variety of data input, output and analysis routines as well as links to hydrological and water resource simulation models.

3.2 New Components

Modifications to the Pitman model went through a series of development iterations. The first version of the modified Pitman model with more explicit groundwater interaction routines was published by Hughes (2004). The original model focussed on the recharge and groundwater discharge (to streamflow) components and assumed groundwater levels were always above the channel (or at the same level). The initial revised model then went through several testing phases and development iterations to account for other processes. As a result, the revised model should be applicable to more catchment situations than the first version.

The additional components focussed on allowing for situations where the groundwater level could drop below the river channel through riparian evaporation losses and sub-surface outflow to down-gradient catchments, as well as accounting for abstraction losses. One consequence of allowing for the groundwater to drop below the channel was that channel transmission losses could play an important role in the overall water balance. As each component is described, some initial guidelines are provided for establishing parameter values and calibrating the new model parameters, as well as adjusting some of the original model parameters relative to the default values given in WR90. Many of the parameter estimation approaches were based on groundwater variables compiled by Conrad (2005). These were supplied as integrated values for all quaternary catchments in the country.

3.2.1 Recharge

The basis of the recharge component is that the surface characteristics can be represented by a single storage given 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 with the ratio of current storage to the maximum storage (Equation 2).

$$\mathbf{RE = GW\ \{(S - SL) / (ST-SL)\}^{GPOW}} \qquad \mathbf{(2)}$$

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 runoff generated from soil moisture 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 (Figure 3).

There are indications that the parameter SL can be fixed at 0, as the quantities of recharge at low soil moisture levels is normally small and not very important in the whole water balance. There are no direct methods of estimating GW and GPOW from a knowledge of the expected mean annual recharge. This is largely because of the highly non-linearity of the recharge process and its close association with the other outputs (interflow and evapotranspiration losses from the soil water storage, S). It has been found that under most circumstances GPOW can be set to a fixed value of 3.0, after which GW is set to generate an ‘acceptable’ mean annual recharge value.

Intuitively, it might be expected that the original model parameter FT, which determines the maximum amount of interflow, should reduce as the maximum recharge parameter (GW) is increased. The reasoning for this would be that in the original model interflow included groundwater as a sub-component. Several tests suggest that FT should be reduced in some cases (mainly drier catchments), while in others it is not necessary to reduce this parameter. Inevitably, as the parameter GW is increased, outputs from the soil moisture store S are reduced, hence reducing interflow without modifying the FT value.

The GRAII database (Conrad, 2005) provides three estimates of recharge:

- Outputs from the recharge component of the GRAII project
- Outputs from the surface – groundwater interaction component of the GRAII project
- Outputs based on estimates from the DWAF RDM office.

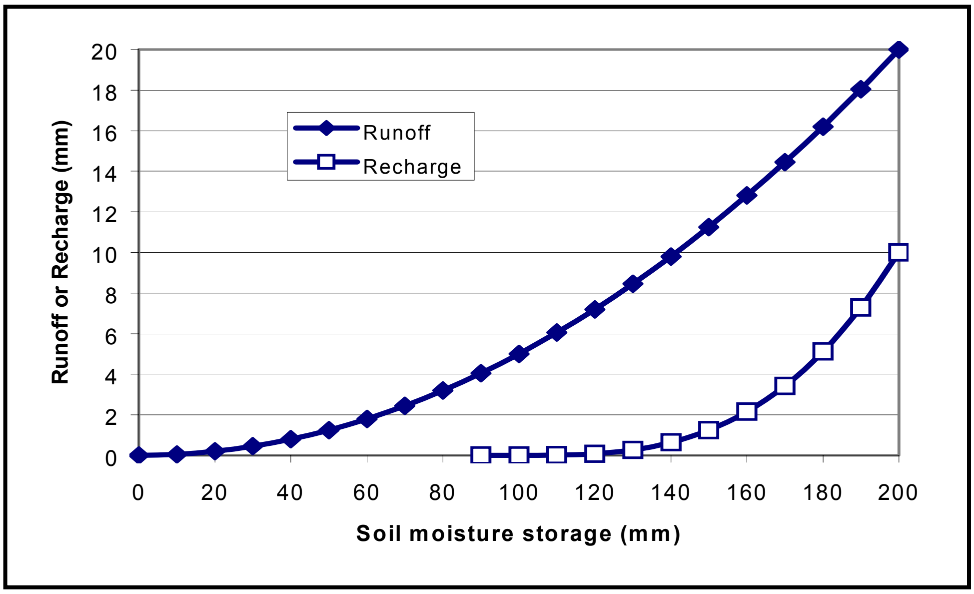

Figure 3: **Illustration of the original soil moisture runoff function (with parameter ST=200, SL=0, FT=20 and POW=2) and the additional recharge-moisture state relationship with parameter SL=100, GW=10 and GPOW=3.**

In general, the first estimate is normally the highest and that from the surface – groundwater study the lowest. Initial tests of the revised Pitman model suggested recharge values slightly higher than those derived from the surface – groundwater study were most appropriate[1].

3.2.2 Groundwater Discharge to Streamflow

When considering groundwater discharge to streamflow, the following issues need to be considered:

- Geometry of the groundwater store
- Riparian losses to evapotranspiration
- Discharge to downstream catchments

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[1] The 'most appropriate' has been based on calibrating the model against the existing WR90 simulated flows (generated using the original Pitman model) and therefore is also based on the 'conventional wisdom' regarding total baseflow contribution that formed part of the WR90 study (Midgley et al., 1994). This has yet to be confirmed through consultation with other experts in the field.

3.2.2.1 Geometry of the groundwater store

The first principle that had to be established was to determine the approach to the water balance within the groundwater storage zone, and hence which model components would determine the effects of inflows and outflows to this zone.

The basis of this component is to reduce the complexity of the spatial geometry of the basin to a simple geometric arrangement. The starting point is to represent the basin as a rectangle (the first version of the model assumed a square) and the channels as parallel lines, separated by drainage slopes. The drainage slopes consist of the two areas between the edges of the rectangle and the outermost ‘channels’, plus two between each ‘channel’ line (Figure 4). Drainage is assumed to be 1-dimensional for simplicity. The number, length and width of the drainage slopes are determined from basin area and effective drainage density. The channels included in the effective drainage density are those that can be considered to be the main recipients of groundwater discharge and could exclude smaller tributary channels that actively flow only during storm events. Effectively drainage density is a model parameter that can be inferred (but probably not measured directly) from maps and an approximate understanding of the basin characteristics. The number of channel lines can be calculated from:

Total channel length = Drainage density * Area (3)

The ratio of catchment width and length is assumed to be related to drainage density as follows:

Width = Length * 2.0 * Drainage density (4)

Therefore:

Length = SQRT(Area / (2 * Drainage density)) (5)

By definition (and from Figure 4):

Number of drainage slopes = 2.0 * Drainage density * Area / Length (6)

The number of drainage slopes is equal to 2 * number of channels. However, Equation 6 has to be corrected to generate an even integer number of drainage slopes, each of which has a width given by:

Drainage width = Width / No. of drainage slopes (7)

Figure 5 illustrates the situation for a single drainage slope and the volume of the ‘wedge’ of groundwater stored under that drainage slope (assuming that the lower boundary is the channel at the bottom of the slope) can be calculated as:

‘Wedge’ volume = (Drainage width)^{2} * Gradient * Drainage length / 2 (8)

Where ‘Gradient’ is the hydraulic gradient of the groundwater flowing toward the river channel (or away from the channel when the groundwater is below the channel).

Volume of water in ‘wedge’ = ‘wedge’ Volume * Storativity (9)

Outflows from this wedge to the river channel, within a single slope element can be calculated:

Discharge = Transmissivity * Gradient * Time step * Channel length (10)

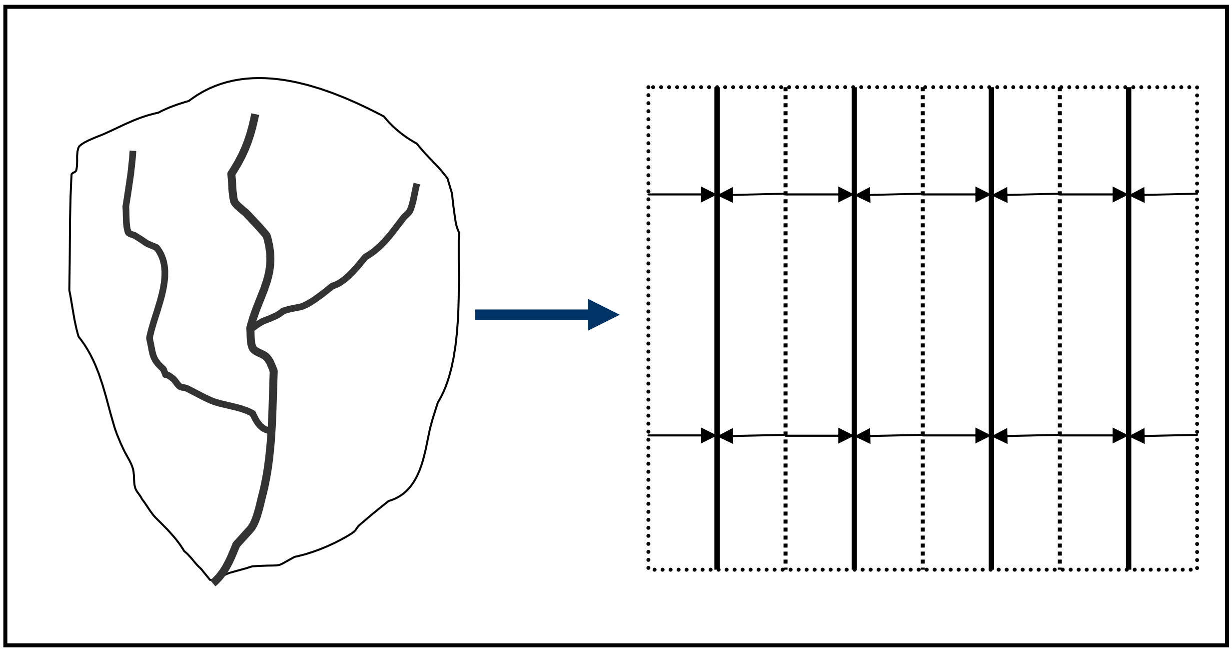

Figure 4: **Conceptual simplification of drainage in a basin for a drainage density of 4/SQRT(Area) (solid lines are channels, dashed lines are drainage divides and arrows show drainage directions). In this illustration there are 8 drainage slopes.**

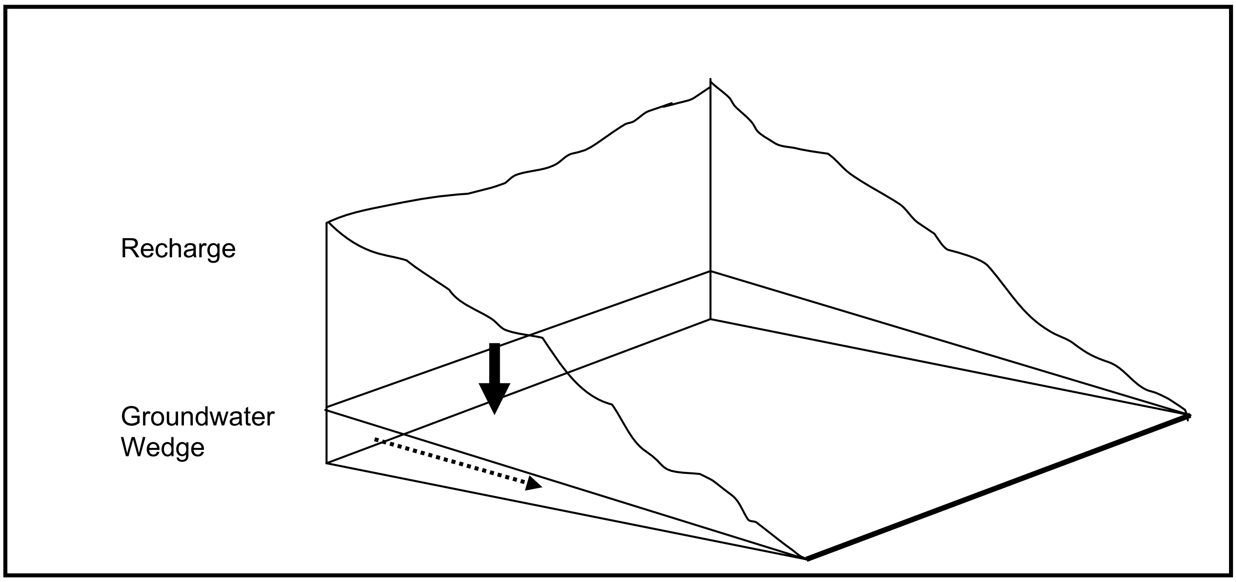

Figure 5: **Illustration of a single drainage slope element. The thick arrow indicates recharge water from the surface to the groundwater 'wedge', the thin arrow indicates the direction of drainage. The 'wedge' represents the part of the groundwater body that is above the conceptual river channel and can contribute to discharge.**

Additional changes for the current version of the modified Pitman model involved addition of abstraction routines and channel transmission losses (i.e. channel flow contributions to groundwater). It was noted that the response to abstractions could be different in near-channel areas to those that occur in areas distant from the channel. To allow for this, the model was modified so that the total slope element is divided into two parts with the downslope gradient in each part calculated separately. The upper slope (or 'far' from the channel) part is set at 60% of the total slope width while the down slope (or 'near' to the channel) part is 40% of the width. The recharge input and down-catchment outflow (see later) are proportionally divided (i.e.

60:40) for the two slope components. This means that the geometry of the two 'wedges' of groundwater are estimated separately during each time interval. The process within each model iteration step (4 per month) is as follows:

- Recharge is calculated and the associated volume of water added to the upper and lower wedge storage volumes.
- Gradients from the previous step are used to estimate outflow from the upper slope component to the lower slope component, the outflow from the lower slope component to the channel and the regional groundwater gradient used to calculate the outflow to the downstream catchment (see later). The riparian evapotranspiration losses are calculated (see later), as are any channel transmission loss inputs to groundwater and any abstraction losses from groundwater.
- The new volumes of water in the two slope elements are then used to estimate the gradients for the next time step.
- It is assumed that the lower slope end point is fixed at the river channel and the gradient calculated from 40% of the width and the volume (which can be negative and therefore so can the gradient).
- From the previous calculations, the upper slope end point, where it joins the lower slope element can be determined and therefore so can the gradient of the upper slope element from the upper slope volume and simple geometry.

While the proposed geometric representation of groundwater flow towards a river channel is very simplistic and ignores many of the realities of groundwater movement, it is nevertheless useful as most of the calculations are simple geometric equations. It should be noted that the initial hydraulic 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 hydraulic gradient that changes as groundwater 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 results in more outflow in the future.
- If drainage is greater than recharge, then the outflow will gradually decline.
- Lower drainage densities result in less outflow.

There is no longer a need for a groundwater lag routine (using the parameter GL in the earlier version of the model), as the new groundwater function also acts as a routing reservoir.

Once the new model was coded, several checks were undertaken to ensure that a water balance was achieved. This was essentially straightforward as the main water balance issues are confined to surface storage and groundwater 'wedges'. As long as recharge is correctly removed from the surface storage and correctly added to the 'wedge', and the 'wedge' volume correctly updated after drainage, there will be a water balance within the model.

It should be noted that in some circumstances the groundwater and surface water divides of a basin are not the same, and regional groundwater flows may dominate drainage processes. In such cases the model formulation would not be appropriate. This is not generally the case in the southern African region where fractured rock aquifers dominate.

It was stated earlier that the initial value of the groundwater gradient is not all that important as the model 'warms up' and determines gradient changes that are dependent on other parameters (GW, GPOW, Storativity, Transmissivity and Drainage density). However, there can be problems interpreting the first few years of results if the starting value is very different to the valid range of gradients. To resolve this issue without adding a parameter for the starting value, the model is ran twice. The starting gradients (upper and lower slope elements) in the first run are set to the regional groundwater gradient (used for downstream outflows – see later), while the final gradients at the end of the first run become the starting gradients for the second model run.

3.2.2.2 Riparian losses to evapotranspiration

It was assumed that groundwater can be subject to evapotranspiration losses close to the channel margin (either through use by riparian vegetation or evaporation from channel beds and banks). A model parameter was added and is referred to as the Riparian Strip Factor (RSF). This is the percentage of the total slope element width over which evapotranspiration losses are assumed to occur and while the lower slope element gradient is greater than zero, the losses are assumed to occur at the potential evaporation rate. A further parameter (Rest Water Level - RWL) was added that refers to the maximum depth below the channel that the connecting point between the upper and lower slope elements can reach before the groundwater is considered to be inaccessible to all groundwater outflow processes (discharge, abstractions and evapotranspiration). This depth is translated into a gradient (necessarily negative) that can be used to estimate a depletion factor, when the current lower slope element gradient is less than zero:

GW depletion factor = (gradient at RWL – current gradient) / gradient at RWL **(11)**

Evapotranspiration losses are reduced by this depletion factor (see Eq. 12). If there is a positive value for groundwater discharge to the channel, this is first reduced by the evapotranspiration losses and if there are still losses to account for, the groundwater volume (and hence the gradient) is reduced.

Evap. losses = Drainage Width * Net Evap. * Riparian Strip Factor * Depletion Factor **(12)**

Net evaporation refers to the difference between potential evaporation demand and rainfall and negative values (i.e. where rainfall exceeds potential evaporation) are corrected to zero (to avoid duplicating the recharge function over the riparian strip).

3.2.2.3 Discharge to downstream catchments

A regional groundwater gradient parameter is included that refers to the gradient appropriate for estimating outflows from one sub-catchment to the next one downstream. The same basic flow equation (Eq. 11) is used:

Downstream outflow = Transmissivity * Regional gradient * Time step * slope width **(13)**

The total outflow for a subcatchment would then be the result of equation 12 times the number of slope elements. Clearly the influence of the drainage density on the catchment width/length ratio will have a major impact on the volume of downstream outflow. The outflow is reduced by the GW depletion factor (Eq. 11) when the lower slope element gradient is negative.

Previous comments about the lack of correspondence between the surface and subsurface water drainage systems need to be recognised. However, given the level of detail that is contained within the model, as well as the amount of information commonly available, it was not considered appropriate to add additional parameters that could account for differences in routes of water movement in the surface and sub-surface environments.

To be able to quantify the groundwater discharge to stream flow, the following need to be quantified:

- Transmissivity
- Storativity
- Drainage density
- Regional GW drainage slope
- Rest water level
- Riparian strip factor (% of slope width)

Transmissivity and *storativity* can be taken from the existing GRAII database of groundwater parameters (Conrad, 2005) and only adjusted if the individual model user considers the database values to be incorrect or inappropriate for the specific study. The storativity value in the database can be used directly, while half of the interpolated transmissivity values appears appropriate.

Drainage density can be set at an initial value of 0.4 for most headwater catchments that do not have any specific shape characteristics. If they are elongated and the transmissivity parameter is high, it is probably sensible to reduce the drainage density (to 0.3 or even 0.2) to ensure that outflow volumes to the downstream catchment are not excessive. Reducing the drainage density can also be used to smooth the variations in groundwater discharge to surface water (as can increasing the storativity). For downstream catchments, lower drainage densities appear to be appropriate (0.2 to 0.3). Note that drainage densities higher than about 0.5 should not be used unless there is extremely good justification.

The *regional groundwater slope* does not seem to need to vary very much between catchments and provisional estimates suggest that a value of close to 0.01 will be satisfactory in most catchments. There is very little information available on this process at the scale of quaternary catchments and the drainage density parameter is likely to influence the volumes as much as any other parameter. The initial parameter estimates were based on the following equation where the catchment average slope values (as a percentage) in the GRAII database were greater than 1 (in other cases the GW drainage slope was taken as the catchment average slope/100:

$$\textbf{Regional GW drainage slope} = (\textbf{catchment average slope})^{0.05} / 100 \qquad \textbf{(14)}$$

The *rest water level* parameter can be taken from the existing database of groundwater information (using the variable ‘median saturated thickness’, Conrad, 2005) and is not a very sensitive parameter in the model. However, extreme parameter values should be avoided (i.e. less than 10 m and greater than about 50 m) to avoid problems with the variation in the groundwater depletion factor calculation.

3.2.3 Channel Losses and Groundwater Abstractions

The final changes incorporated into version 3 of the model involved addition of abstraction routines and channel transmission losses (i.e. channel flow contributions to groundwater). The addition of these new components was the main motivation for dividing each slope element into two parts; the upper (or far from the channel) and the lower (or close to the channel). To avoid adding any new parameters the upper element is taken as 60% of the total slope element width, and the lower as 40%.

The principles are that the water balance calculations are first performed on the lower slope component, and the lower slope and position of the junction point fixed. The water balance calculations are then performed on the upper slope element and the gradient of the upper slope fixed for the start of the next time interval. An assessment of the differences between the single slope element version of the model and the revised, two element version suggested the two slope approach will give almost identical results when there are no abstractions and channel losses.

3.2.3.1 Channel transmission losses

It was recognised that when the groundwater level drops below the level of the channel (a negative downslope gradient in the model), it is possible that losses will occur from the channel back to the aquifer and that the rate of loss will be due to some characteristics of the channel (unknown), the head difference between the channel and the groundwater and the transmissivity of the material under the channel. It is not really possible to estimate these in practical situations and it is also necessary to minimise the number of additional parameters (enough new parameters have already been added).

It is also important to recognise that there are two components of channel loss in downstream catchments (i.e. where there are sub-catchments upstream that generate inflows into the current catchment being modelled). The first component is channel losses from the runoff generated within that catchment, while the second component is channel loss from flow in the main channel.

The following scheme has been adopted for the **channel losses to flow generated within the catchment** (the incremental runoff).

The value of a variable MAXQ (mm) is estimated during the first run of the model (it is set to 20 mm at the start of the first run) and a further variable TLQ estimated from the current months runoff (Q) and the following equations (see Figure 6):

If $Q/MAXQ < 0.3$

$$TLQ = 0.5 * (\tanh(10 * (Q / MAXQ - 0.2)) + 1.0) \qquad (15)$$

If $Q/MAXQ \geq 0.3$

$$TLQ = 0.5 * (\tanh(2.5 * (Q / MAXQ - 0.2)) + 1.0) \qquad (16)$$

A further variable (TLG – see Figure 7) is estimated from the current gradient relative to a maximum gradient defined by 0.7 of the gradient at the ‘Rest Water Level’ (RWLGrad).

If $Gradient < 0.7 * RWLGrad$ then

$$TLG = TLGMax \qquad (17)$$

If $Gradient \geq 0.7 * RWLGrad$ then:

$$TLG = TLGMax * (Gradient / (0.7 * RWLGrad))^{0.25} \qquad (18)$$

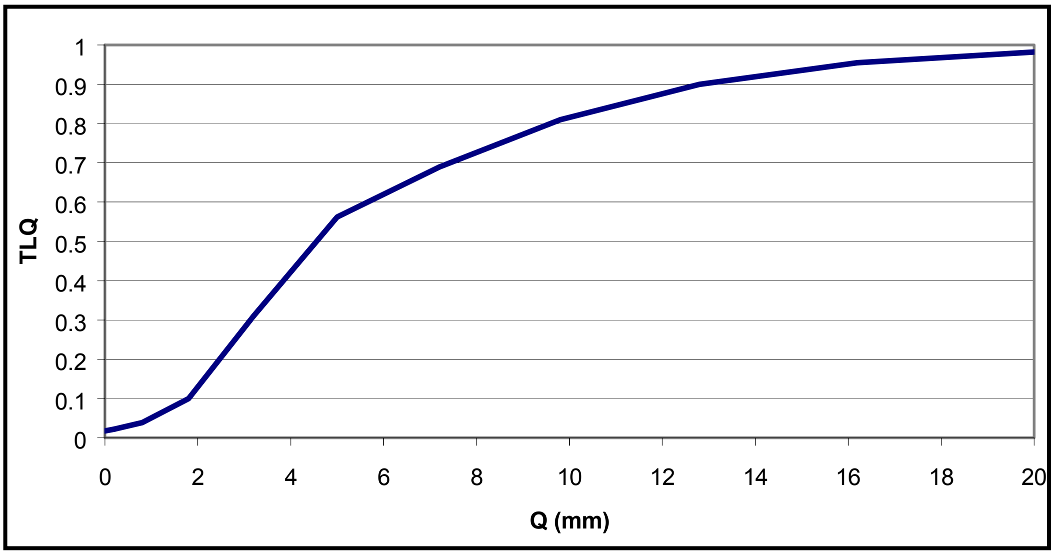

Figure 6: **Shape of the power relationship between current month discharge (mm), relative to a maximum value (20 mm in this case) and a model variable, TLQ.**

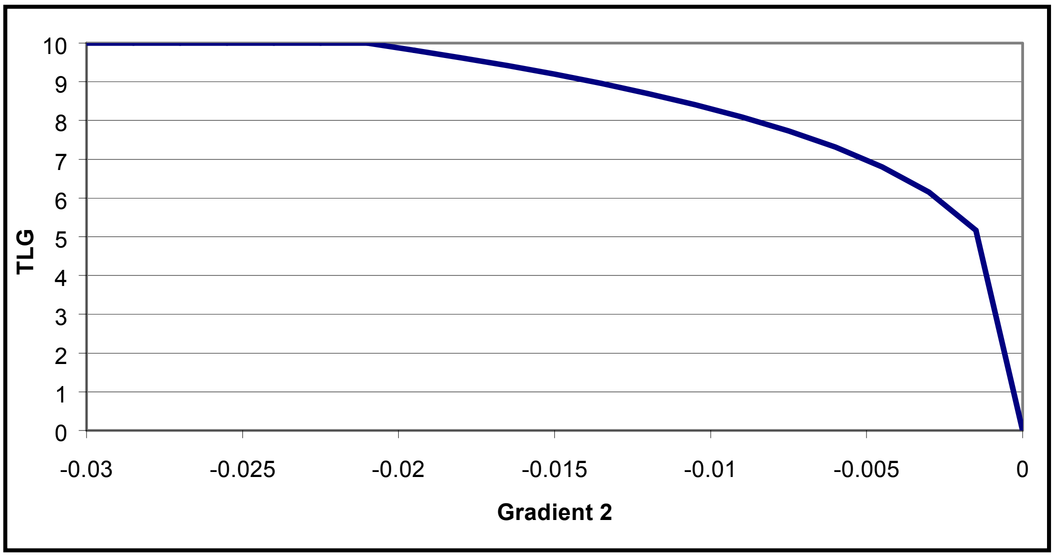

Figure 7: **Shape of the power relationship between current downslope gradient and a model variable, TLG. The maximum value of TLG is defined by a model parameter.**

Channel loss (mm) is then the product of TLQ * TLG, which is removed from any available runoff and added to the lower slope component. There are a number of constants in equations 14 to 17 that have been fixed in the current version of the model to avoid introducing additional parameters that will be very difficult to quantify. The only additional parameter is therefore TLGMax, the maximum channel loss (expressed as runoff from the whole sub-catchment in mm). This maximum loss will occur when the lower slope gradient is at 70% of the gradient at the rest water level and when the sub-catchment runoff is at its maximum value.

As already noted, the previous channel loss routine only applies to incremental runoff generated within the sub-catchment of the distribution system and NOT to upstream runoff that passes through that sub-catchment. To manage cumulative flow channel losses without adding additional parameters, the same functions as described above for sub-catchment channel losses has been used, but applied to the upstream inflow to the sub-catchment. The GW gradient component of the function remains the same (equations 16 and 17), except that TLGmax now represents a maximum channel loss from upstream inflow (in $m^3 * 10^6$). TLGmax_Inflow is calculated from the TLGmax parameter for incremental flow using the following scheme:

$$\mathbf{TLGmax\_Inflow = TLGMax * (MAXQ\_Inflow / MAXQ)} \qquad \mathbf{(19)}$$

Where MAXQ is defined previously as the maximum sub-area runoff (mm) and MAXQ_Inflow is the maximum upstream inflow. Both of these are set to initial values in the first run of the model (MAXQ = 20 mm, MAXQ_Inflow = 20 mm * cumulative upstream catchment area) and are then re-calculated for the second run from the data simulated during the first run.

Equations 15 and 16 are also used to estimate the TLQ component, but with MAXQ replaced by MAXQ_Inflow and Q defined as the upstream inflow in any one month. The cumulative inflow channel losses are estimated at the start of a single month's simulation and reduce the upstream inflow (there is no iteration of this calculation). The additional volume is then added to the near channel (or lower element) groundwater storage in equal amounts over the model iteration steps (fixed at 4 in the current version of the model).

Clearly, this function has no impact on headwater catchments that have no upstream inflow. There are potential problems with the function related to the simplified GW geometry as defined by the drainage density parameter and illustrated in Figure 4. The division of the catchment into slope elements represents all the channels, while upstream inflow losses should only apply to the main channel. However, in reality sub-catchments that experience significant main stem channel losses would probably not have internal catchment tributaries that are likely to generate GW flow. The assumption is that the effective channel network and drainage density for the purposes of GW-SW interaction would be made up only of the main channel. In that case the drainage density would be low and the ratio between catchment width and length also relatively low, which should be a reasonable reflection of reality.

Recent modifications to the model have changed the shape of the Q – TLQ curve shown in Figure 6. The effects of these changes are to generate a higher value of TLQ at low runoff values (Q tending towards 0). After some re-evaluation of the model, equations 15 and 16 were not considered realistic as very little channel loss was generated for any groundwater condition. The revised version of the transmission loss routine is still being evaluated. The original version is retained in this report as this was the version that was used in the tests discussed in Section 4.

3.2.3.2 Abstractions

Abstractions are allowed for as annual volumes and seasonal distributions from both the near channel and remote environments. There are therefore two additional water use parameters which represent the abstraction volumes in $m^3 * 1000$ from all the upper and lower slope elements. An additional column has also been added to the monthly distribution data requirement, which represents the seasonal distribution of GW abstractions (the same distribution is applied to both abstractions).

3.2.3.3 Parameter estimation

The only additional parameter (apart from the abstraction volumes) is the TLGMax value which represents the maximum possible channel loss and is used for both the loss routines. This will always be a difficult parameter to quantify, but fortunately will only be relevant to a relatively small number of catchments in the country. However, it is important that this parameter is not ignored in dry regions where the groundwater lower slope element gradient will be nearly always negative. If the TLGMax parameter is set too high relative to simulated runoff depths it is possible that a large part of the runoff generated from other model components could be lost to groundwater.

The use of TLGMax for both loss functions might be considered problematic. However, where there are major losses from upstream runoff, there is likely to be very little incremental flow within the sub-catchment. The value of TLGMax will therefore be dominated by the range of values of upstream inflow, rather than local runoff.

3.3 Some Initial Observations

Several test runs of the revised version of the model were assessed for the credibility of the results and the extent to which the model can reproduce the time-series of WR90 flows with minimal changes to the WR90 parameters. In terms of calibration, it was found that only small changes were necessary to the original WR90 parameters to achieve the same time series of flow as WR90 when ‘sensible’ groundwater parameters were used in the model. The main parameter to change is the FT parameter (normally reduced as this already accounts for baseflow to a certain extent). In the arid areas tested no changes to the original model parameters were found to be necessary at this level of testing.

An initial test of the abstraction components and the effects on the gradients within the two slope elements was undertaken on catchment X12A. Figure 8 indicates what happens in the model when there are no abstractions and when abstractions of 5 $*10^6$ m^3 are included from the upper and lower slope elements. The parameters of the model have been set as Transmissivity = $8m^2$ d^{-1}, Storativity = 0.002. Recharge for the whole catchment is 8.487 $*10^6$ m^3 (or 5.092 over the upper element and 3.395 over the lower element). This means that the abstraction over the upper element represents almost all the recharge, while over the lower element it represents far more than the local recharge (but remember that the lower part is fed by downslope flow from the upper part).

The gradient diagram shows the range of gradients in the two slope parts under the three different scenarios. Note that for no abstraction the gradients in the two parts are always similar and positive. For lower abstractions the gradient in the lower part becomes negative under dry (low recharge) conditions and therefore discharge to the channel ceases. Under the upper abstraction scenario, the gradient in the lower part is always positive (although quite small under dry conditions), while the upper part gradient is highly negative under dry conditions. The model does not transfer water from the lower part to the upper part under these conditions.

It is necessary to recognise that the model simulates abstraction conditions that are assumed to be always present. It does not simulate what will happen if abstractions are suddenly implemented. It is the immediate impacts after the start of abstraction that will be very different for abstractions that are made close to or distant from the channel. In the long term, water balance considerations suggest that the effects should be similar regardless of where the abstractions occur (they are both intercepting recharge water that would have contributed to GW discharge). However, there are still some differences due to the changes that occur to the evaporation losses in the lower slope element. The table below shows the impacts on discharge to the channel, while Figure 9 shows the effects on the duration curves of GW discharge.

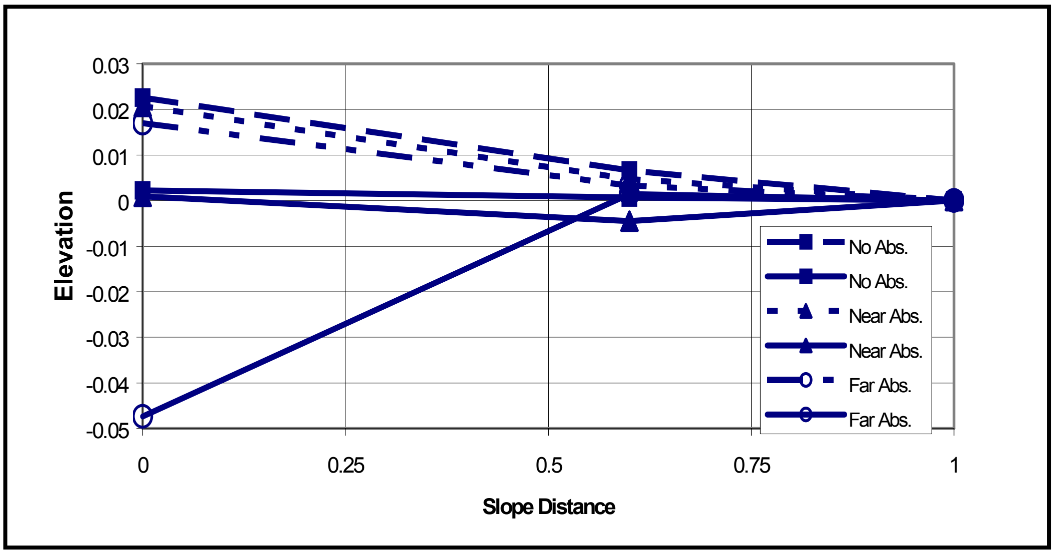

Figure 8: **Range of gradients under model scenarios of no abstraction and abstractions from the upper (or 'Far') and lower (or 'Near') slope elements. The distance and elevation units are non-dimensional and expressed relative to the total slope length**.

Table 1: **Impact of abstraction on discharge to channel.**

Scenario	No. Abs.	Upper element Abs.	Lower element Abs.
Mean annual GW discharge (10^6 m^3)	8.264	3.486	3.272

The main thing to note and consider is that the difference in mean volumes of outflow between the two scenarios is quite small, but the effect on the GW discharge duration curves is quite large. This effect gets smaller if the Transmissivity (T) parameter is reduced (to say 4), and gets larger if T is increased.

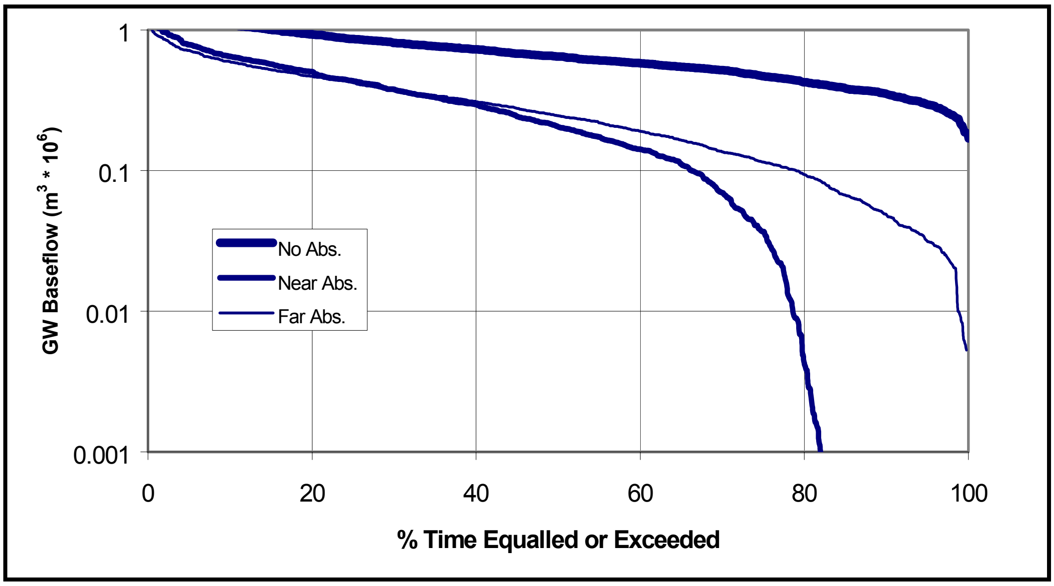

Figure 9: **Duration curves of GW discharge to streamflow under the three scenarios of abstraction.**

The GW parameters for X12A were modified slightly during a group workshop between Messrs Hughes, Sami and Parsons to generate what were considered more realistic conditions. The main change was to the storativity (changed to 0.01) and the result was that the GW contribution changed to $5*10^6$ m^3 out of a total mean annual runoff of $26.3*10^6$ m^3 (or 19%). The next phase was to assess the routines for estimating channel losses and the first test of this involved introducing a $4*10^6$ m^3 abstraction from the lower slope element. Before channel transmission losses were introduced, the abstraction reduced the GW contribution to $1.06*10^6$ m^3 and the MAR to $22.36*10^6$ m^3. After channel losses were introduced with a TLGMax parameter of 20 mm (about 10% of maximum runoff depth) the GW contribution increased to $1.25*10^6$ m^3 and the MAR reduced slightly to $22.33*10^6$ m^3. The GW contribution increases as the gradient in the lower slope element does not reach very high negative values (meaning that recharge does not have to make up the deficit before discharge can occur), while the other differences are related to changes in the water balance between the two slope elements and the evaporation losses from the riparian strip. The time series of effects appear to be reasonably sensible.

To simulate a situation of intermittent natural GW flow, the recharge parameters were reduced until the lower slope element gradient was positive for approximately 35% of the time. Before introducing the channel loss parameter, the resulting MAR was simulated as $21.85*10^6$ m^3 with only $0.18*10^6$ m^3 being GW contribution. After introducing a TLGMax parameter of 20 mm, the MAR reduced to $21.62*10^6$ m^3 and the GW contribution increased to $0.41*10^6$ m^3, largely due to the fact that the lower element gradient now fluctuates around zero.

Quaternary catchment Q92F was simulated using the standard WR90 regional parameters with a limited amount of recharge (2.7 mm from an MAP of 407 mm). Without channel losses, the upper element gradient varies around weakly positive values (0.5%), while the lower element gradient varies around –1.2%. The simulated MAR is $3.98*10^6$ m^3 and the maximum month runoff depth approximately 49 mm. Introducing a channel loss parameter (TLGMax) of 4 mm (10% of maximum monthly runoff depth), reduced the MAR to $2.99*10^6$ m^3. The lower element gradient now fluctuates over a wider range with an average of about –1%, while the effects on the upper element gradient is small but largely confined to more variation. The results appeared to make intuitive sense, although in reality the WR90 parameters for the original model would now require some modification.

In general terms the revised algorithms appeared to generate results that were intuitively realistic. However, further testing was required and guidelines developed for quantifying the new parameter values and re-evaluating some of the original parameter values. It was also necessary to critically review the values of the two fixed-value power variables in the channel loss routines.

4 CALIBRATION TESTS

The purpose of the initial tests of applying the new groundwater algorithms was to develop some guidelines for initial parameter estimation and model calibration and to assess the validity of the model outputs across a range of catchments within South Africa. The following issues need to be recognised and taken into account when interpreting the results of these initial calibration tests:

- The model was calibrated against the existing WR90 (Midgley *et al.*, 1994) simulated monthly time series data and making use of the same catchment average rainfall inputs and seasonal distribution of potential evaporation demand. This means that any assumptions, particularly about the total baseflow response, that were made during the calibration of the original model are necessarily relevant to the new model assessments.

- The WR90 regional values of the parameters of the original model that are still part of the new model were retained and only changed during the calibration process if absolutely necessary. This is mainly relevant to the FT parameter, which in the original model is the main driver of baseflows. Baseflows in the new model are made up of 'interflow' (mainly driven by the FT and POW parameters) and 'groundwater contributions to baseflow' (driven by the new parameters described in Section 3).
- The initial parameter values of the groundwater components of the model were derived (wherever possible) from the national database of groundwater characteristics developed by Conrad (2005) from various original sources.

4.1 Initial Parameter Estimates

GIS data presented by Conrad (2005) was summarised as quaternary catchment values for all of the variables listed in Table 2 using mean or median values from the gridded data. Table 3 summarises the new groundwater parameters of the model and the first step in the model testing process was to use information from the GRAII database to provide initial estimates for as many of the parameters in Table 3 as possible.

SL represents the soil moisture storage level below which groundwater recharge is considered to cease. While intuitively it may be expected that this parameter could be important in limiting the amount of recharge during dry periods or seasons, it would be very difficult to determine an initial estimate. The non-linear nature of the groundwater recharge – moisture storage function suggests that at low storages the recharge is usually quite small and it has therefore been assumed that this parameter value can be set to 0.

GW represents the maximum monthly recharge rate that will occur when the moisture storage level is at its maximum (ST – a parameter in the original model). The relationship between this parameter value and annual recharge is complex and non-linear. It is therefore difficult to make use of any of the GRAII database variable values to derive a precise parameter estimate. However, for the purposes of an initial estimate it has been assumed that the average value of S/ST is 0.65 and therefore GW can be estimated from:

$$\mathbf{GW = (Annual\ recharge\ /\ 12)\ /\ (0.65)^{GPOW}} \qquad \mathbf{(20)}$$

There are three annual recharge estimates given in the GRAII database (RECHP, MEAN_KS and MEAN_RDM – see Table 2). All of these are very different with RECHP generally being much higher and MEAN_KS generally being the lowest value. The first step in the model calibration process is usually to adjust the GW value until an acceptable annual recharge depth is achieved. The problem then becomes to decide which of the three recharge estimates can be considered acceptable.

GPOW is the power of the relationship between S and recharge and has been fixed at 3.0 for the purposes of initial parameter estimation.

DDens represents the effective drainage density of the channels receiving groundwater contributions and there are no database values upon which to base an estimate of this parameter value. Initial estimates have therefore been fixed at 0.4. It is however, assumed that this will be reduced for catchments with elongated shapes (low width/length ratios) and dry catchments that are not expected to have extensive channel networks that interact with groundwater.

Table 2: Data contained within the GRAII database for all quaternary catchments.

SYMBOL	DESCRIPTION
CATNUM	Quaternary catchment no as per WR90
AREA_M2	Area in m^2
CMAP	CMAP from WR90
MAP_MM3	MAP in Mm^3 calculated from CMAP
MAR	MAR from WR90
TOTAL_USE	Total GW use Mm^3 from GRAII
USEOFRECH	Use as a percentage of calculated recharge (uncalibrated GIS method output_
SLOPE	Mean slope per catchment (degrees) calculated from 1x1 km grid based on DWAF DTM
MEAN_SLP_P	Mean slope per catchment (percentage) from 1x1 km grid based on DWAF DTM
MEAN_SSATI	Mean SSATI per catchment from Vegter's SSATI dataset
MED_SSATI	Median SSATI per catchment from Vegter's SSATI dataset
MEAN_STHK	Mean saturated thickness from Vegter 1995. The mean thickness of that part of the saturated zone which contains the bulk of the most readily accessible groundwater was taken on average to be half the optimal drilling depth below the water level.
MED_STHK	Median saturated thickness per catchment from Vegter 1995
MEAN_TRANS	Mean transmissivity per catchment - Transmissivity (m^2/day) derived from borehole yields (from NGDB & Paul du Plessis)
EBFI	Estimated baseflow index
RECHP	Mean calculated recharge percentage from GRAII - output from GIS calibrated layer
RECH_MM3	Mean calculated recharge volume from GRAII - output from GIS calibrated layer
RECH_MM_feb05	Mean calculated recharge depth from GRAII - output from GIS calibrated layer
RECHMIN_MM3	Minimum calculated recharge volume from GRAII - output from GIS calibrated layer
RECHMAX_MM3	Maximum calculated recharge volume from GRAII - output from GIS calibrated layer
RECHMIN	Minimum calculated recharge percentage from GRAII - output from GIS calibrated layer
RECHMAX	Maximum calculated recharge percentage from GRAII - output from GIS calibrated layer
RECHRNG	Range of calculated recharge percentages from GRAII - output from GIS calibrated layer
MIN_KS	Minimum calculated recharge percentage from GRAII - GIS calibrated against Karim Sami's output
MAX_KS	Maximum calculated recharge percentage from GRAII - GIS calibrated against Karim Sami's output
MEAN_KS	Mean calculated recharge percentage from GRAII - GIS calibrated against Karim Sami's output
MIN_MM3_KS	Minimum calculated recharge volume from GRAII - GIS calibrated against Karim Sami's output
MAX_MM3_KS	Maximum calculated recharge volume from GRAII - GIS calibrated against Karim Sami's output
MEAN_MM3_KS	Mean calculated recharge volume from GRAII - GIS calibrated against Karim Sami's output
MIN_RDM	Minimum calculated recharge percentage from GRAII - GIS calibrated against output from RDM office
MAX_RDM	Maximum calculated recharge percentage from GRAII - GIS calibrated against output from RDM office
MEAN_RDM	Mean calculated recharge percentage from GRAII - GIS calibrated against output from RDM office
MIN_RDM_MM3	Minimum calculated recharge volume from GRAII - GIS calibrated against output from RDM office
MAX_RDM_MM3	Maximum calculated recharge volume from GRAII - GIS calibrated against output from RDM office
MEAN_RDM_MM3	Mean calculated recharge volume from GRAII - GIS calibrated against output from RDM office

Table 3: Parameters of the groundwater components of the modified Pitman model.

PARAMETERS AND UNITS	SYMBOL
No recharge below storage (mm)	SL
Max. Recharge rate (mm/south)	GW
Power : Storage-Recharge curve	GPOW
Drainage density	Ddens
Transmissivity (m^2/day)	T
Storativity	S
Regional GW drainage slope	RG
Rest water level (m below surface)	RWL
Riparian Strip Factor (% slope width)	RSF
Maximum Channel Loss (mm)	TLGMax
GW Abstraction (Upper slopes-Ml y^{-1})	GWA_upper
GW Abstraction (Lower slopes-Ml y^{-1})	GWA_lower

Transmissivity (**T**) values have been estimated as 0.5 * MEAN_TRANS (Table 1) under the assumption that a catchment mean T would be substantially less than an estimate based on borehole yields.

Storativity (**S**) has been estimated directly from the MEAN_SSATI variable within the GRAII database.

Regional groundwater gradient (**RG**) is the gradient used as part of the estimation of down-catchment groundwater outflow. The only slope variables within the GRAII database are associated with mean catchment slope, which is most cases will be much higher than an acceptable regional groundwater gradient. There are several options that could be used to reduce this, most based on a power function with a power of less than 1. The current method assumes that RG = $(\text{MEAN\_SLP\_P} / 100)^{0.05}$ when the mean catchment slope is greater than 1%, otherwise the mean slope is used directly. The result of this is that a large number of the RG parameter values lie in a narrow range close to 0.01.

The rest water level (**RWL**) parameter has impacts on down-catchment outflows and riparian evapotranspiration losses during periods when the groundwater is lower than the channel (negative slope element gradients) and set the limits to abstractions. The values have been estimated directly from the MED_STHK variable in the GRAII database.

The riparian strip factor (**RSF**) can be a very important parameter in that it determines the losses from the groundwater store. There is, however, very little basis for estimating the values and therefore initial estimates assume a fixed value of 0.2%.

The maximum channel loss (**TLGMax**) is similarly difficult to estimate and a nominal value of 2 mm has been used as the initial estimate. This will certainly need adjustment for those catchments where the dominant surface-groundwater interaction process is channel transmission losses. The abstraction parameters are not relevant to this exercise in setting initial estimates of the various parameters as the calibrations assumed natural conditions.

4.2 Calibration Approach

The revised model was calibrated against the WR90 simulated data to ensure compatibility and consistency of output between the original and new versions of the model. Several objective functions were used to compare the results (coefficiency of efficiency based on ordinary values and log-transformed values, as well as comparisons of the ordinary means and standard deviations of monthly flow and the equivalent log-transformed values). The main objective was to ensure that the means and standard deviations were close (within 5% relative errors) with a log-transformed CE of as close to 1.0 as possible.

The first step was to obtain an acceptably representative value for mean annual recharge by adjusting the parameter GW. Given that the GRAII database refers to three possible mean annual recharge rates, it was necessary to decide which one should be used. This point will be discussed further below with respect to individual catchments. The next step was to ensure that the GRAII database values for T and S could be considered acceptable.

The third step was to ensure that the overall pattern of baseflows conformed to the original WR90 patterns of baseflow and that the proportion of groundwater recharge that becomes streamflow should be intuitively sensible. This involved possible adjustments to FT (if necessary), drainage density and the riparian strip factor. In some cases (the drier catchments) adjustments to the maximum channel loss parameter were also required to ensure that channel losses during influent groundwater situations were not excessive.

4.3 Detailed Model Results

Table 4 lists the quaternary catchments and GRAII database values that were used for initial parameter estimations, while Table 5 lists the actual parameter values established at the start of the calibration process, as well as the final calibrated values (second row for each catchment). The parameter values that were modified are highlighted. All of the other parameters of the original Pitman model are as given in the WR90 reports. Table 6 provides a summary of the model results, focusing on the groundwater components, but providing additional information for background or comparative purposes. Brief discussions and explanations of the results are provided below.

Table 4: GRAII database variables for the selected catchments used for model parameter estimation (EBFI has been included for reference purposes).

QUAT CATCH	MEAN_ SLP_P	MED_ SSATI	MED_ STHK	MEAN_ TRANS	EBFI	RECHP	MEAN_K S	MEAN_R DM
A21B	2.09	0.0200	75	52.23	0.60	12.84	4.13	7.32
A23A	2.44	0.0008	10	26.14	0.59	14.28	6.06	8.05
A91G	4.84	0.0008	10	24.73	0.52	14.53	5.94	8.16
E10A	14.63	0.0008	75	123.00	0.29	14.99	6.06	8.36
E10E	11.59	0.0008	75	63.05	0.28	10.96	2.80	6.40
E10K	7.55	0.0008	75	24.18	0.00	6.82	0.89	4.39
G22F	18.75	0.0008	75	42.14	0.39	19.34	11.14	10.48
J25B	12.52	0.0008	75	72.98	0.30	6.41	0.88	4.18
K90A	9.07	0.0008	75	28.10	0.41	10.90	2.81	6.37
K90D	2.87	0.0008	75	33.26	0.41	10.48	2.55	6.16
Q92F	2.72	0.0008	10	83.64	0.00	3.06	0.15	2.56
Q94A	10.37	0.0040	25	29.12	0.43	12.91	4.21	7.35
Q94F	3.99	0.0040	25	27.13	0.03	6.44	0.81	4.19
V60A	4.97	0.0008	25	4.59	0.38	12.13	3.57	6.97
V60F	8.05	0.0040	25	8.55	0.35	11.39	3.08	6.61
X31A	11.16	0.0040	25	18.86	0.75	16.99	8.13	9.34

Table 5: Parameter values used in the model exercises (the second rows for each catchment lists the revised parameters after calibration and the values in bold are those that changed during the calibration).

QUAT CATCH	ST	FT	GW	GPOW	DDENS	T	S	RG	RWL	RSF (%)	TLG Max
A21B	300	3	13.0	3	0.4	26.1	0.02	0.010	75	0.2	2
		3	**30.0**	3	**0.3**	**85.0**	0.02	0.010	75	0.2	2
A23A	160	8	19.7	3	0.4	13.1	0.0008	0.010	10	0.2	2
		5	**10.0**	3	**0.2**	13.1	**0.001**	0.010	10	**0.1**	**1**
A91G	100	50	23.9	3	0.4	12.4	0.0008	0.011	10	0.2	2
		50	**55.0**	3	**0.25**	12.4	**0.001**	0.011	10	**0.1**	2
E10A	140	75	25.4	3	0.4	61.5	0.0008	0.011	75	0.2	2
		75	**50.0**	3	**0.3**	61.5	0.001	0.011	75	**0.1**	2
E10E	140	75	5.5	3	0.4	31.5	0.0008	0.011	75	0.2	2
		75	**40.0**	3	**0.25**	31.5	**0.001**	0.011	75	**0.1**	2
E10K	100	0	1.2	3	0.4	12.1	0.0008	0.011	75	0.2	2
		0	**10.0**	3	**0.2**	12.1	**0.001**	0.011	75	**0.1**	2
G22F	270	100	76.2	3	0.4	21.1	0.0008	0.012	75	0.2	2
		100	**120.0**	3	**0.3**	21.1	**0.001**	0.012	75	0.2	2
J25B	100	10	1.3	3	0.4	36.5	0.0008	0.011	75	0.2	2
		8	**40.0**	3	**0.2**	**10.0**	**0.001**	0.011	75	**0.05**	**0.5**
K90A	100	10	9.4	3	0.4	14.0	0.0008	0.011	75	0.2	2
		10	**15.0**	3	**0.25**	14.0	**0.001**	0.011	75	**0.3**	**1**
K90D	250	10	8.2	3	0.4	16.6	0.0008	0.011	75	0.2	2
		10	**15.0**	3	**0.3**	16.6	**0.001**	0.011	75	**0.3**	**1**
Q92F	150	0	0.3	3	0.4	41.8	0.0008	0.011	10	0.2	2
		0	**15.0**	3	**0.1**	**5.0**	**0.001**	0.011	10	**0.1**	**0.5**
Q94A	150	12	15.8	3	0.4	14.6	0.004	0.011	25	0.2	2
		9	**18.0**	3	0.4	14.6	0.004	0.011	25	**0.4**	**1**
Q94F	150	0	1.8	3	0.4	13.6	0.004	0.011	25	0.2	2
		0	**10.0**	3	**0.2**	13.6	0.004	0.011	25	**0.4**	**1**
V60A	120	25	14.9	3	0.4	2.3	0.0008	0.011	25	0.2	2
		20	**13.0**	3	0.4	2.3	**0.001**	0.011	25	**0.4**	2
V60D	120	25	12.8	3	0.4	5.3	0.004	0.011	25	0.2	2
		20	**13.0**	3	0.4	5.3	0.004	0.011	25	**0.4**	2
V60F	120	15	11.1	3	0.4	4.3	0.004	0.011	25	0.2	2
		10	**10.0**	3	0.4	4.3	0.004	0.011	25	**0.4**	2
X31A	600	60	47.1	3	0.4	9.4	0.004	0.011	25	0.2	2
		60	**60.0**	3	0.4	9.4	0.004	0.011	25	0.2	2

Table 6: Summary of Pitman GW model calibrated results.

QUAT CATCH	**AREA (km^2)**	**MAP (mm)**	**RECHARGE**		**MAR**		**RUNOFF COMPONENTS (%)**			**GW (% of recharge)**
			(mm)	(%)	(MCM)	(mm)	Surface	Interflow	GW	
A21B	526.5	671.6	35.9	5.3						
A23A	682.4	696.1	14.8	2.1	28.1	41.2	43.6	33.6	22.7	63.3
A91G	405.8	866.4	97.9	11.3	130.1	320.5	18.6	52.3	29.1	95.1
E10A	133.7	917.4	91.8	10.0	61.1	457.3	40.8	43.4	15.8	78.7
E10E	365.8	427.1	30.2	7.1	51.4	140.5	12.5	70.2	17.3	80.4
E10K	235.0	281.0	10.8	3.8	9.2	39.1	67.9	0.0	32.1	115.9
G22F	65.7	1471.2	175.2	11.9	57.5	875.7	53.0	28.7	18.4	92.0
J25B	396.9	326.3	5.6	1.7	13.3	33.5	85.4	10.6	3.9	23.6
K90A	213.5	714.0	24.2	3.4	29.1	136.3	70.8	20.1	9.1	51.1
K90D	215.2	689.2	22.0	3.2	17.6	81.9	51.8	31.8	16.4	61.1
Q92F	665.7	407.3	3.9	1.0	4.0	6.0	100.0	0.0	0.0	0.0
Q94A	258.9	796.1	33.8	4.2	23.5	90.9	61.4	19.3	19.3	52.6
Q94F	734.1	477.1	4.0	0.8	5.3	7.2	100.0	0.0	0.0	0.0
V60A	106.8	888.5	37.4	4.2	16.8	157.3	27.6	55.3	17.1	71.8
V60D	307.9	847.1	31.0	3.7	36.2	117.7	22.6	60.7	16.6	61.1
V60F	406.0	770.4	21.7	2.8	35.3	86.9	34.1	52.8	13.0	52.3
X31A	230.1	1243.2	135.4	10.9	117.6	511.4	31.0	43.7	25.3	95.6

A21B

This is a dolomitic catchment that seems to have been given special treatment within WR90 as it was not possible to reproduce the baseflow response even with the SPATSIM version of the original Pitman model. The WR90 baseflow response is very flat. It was therefore difficult to develop any basis for continuing with the calibration and the exercise was hence abandoned.

A23A

This quaternary catchment is the upper parts of the Pienaars River east of Pretoria and receives a high volume of return flow from waste water treatment plants. Previous work in this catchment (associated with the determination of the ecological Reserve) had already identified a possible problem with the naturalization process. Calibration was therefore difficult and little could be learned from this catchment. The original GW parameter of the Pitman model was used in both A23A and A21B (see WR90 – Midgley *et al.*, 1994) and this seems to be one of the main reasons why the revised version of the model could not be calibrated to fit the WR90 results.

A91G

This is a tributary of the Luvuvhu River, which is relatively elongated suggesting a lower drainage density than the default of 0.4. The recharge value used lies between the MEAN_KS and RECHP values (closer to RECHP), while the riparian strip factor has been calibrated to be 0.1%. The log CE value is 0.947, while the groundwater contribution to streamflow is a very high percentage of the recharge.

E10A, E and K

These are quaternary catchments of the Olifants River located in the Western Cape. E10A is upstream, E10E is in the middle reaches and E10K is just upstream of the confluence with the Doring River. All of the results are acceptable with log CE values ranging from 0.916 (K) to 0.988 (A). The calibrated recharge values tend to be close to the RECHP values in the GRAII database and the groundwater seems to fluctuate between being effluent (positive slope element gradients) during the wet season, to influent (negative gradients and transmission losses during the dry season). This means that a large part of the dry season baseflow is being generated by interflow in the model, especially in the upper catchment reaches. This is a result that requires further examination with respect to the conceptual understanding of the real hydrological response processes.

G22F

The result for this mountainous Western Cape river is very good with a log CE of 0.988 (similar to E10A). The calibrated recharge value lies close to the MEAN_KS value, in contrast with the results for the E10 catchments. The groundwater is always effluent, although during the dry season months the gradients are very low. It would be useful to compare the model results for this catchment and E10A with conceptual ideas about differences in response.

J25B

This is a tributary catchment of the Gouritz River in the Karoo. However, the regime is almost perennial with less than 5% zero flows. The simulated recharge is quite close to the MEAN_KS value and much lower than RECHP. The log CE statistic is 0.966. Even with a relatively low riparian strip factor the percentage of recharge that contributes to streamflow is still quite small and the groundwater fluctuates between being effluent and influent. The transmissivity value for this catchment was reduced from 36.5 to 10.0 $m^2\ d^{-1}$, while it was also found necessary to reduce the FT value slightly.

K90A and D

These are two quaternary catchments of the Kromme River Eastern Cape. The simulated recharge values are close to the MEAN_KS values and log CE values both better than 0.98. The riparian strip factor for K90A was increased to 0.3% to account for the presence of substantial wetland areas in the valley bottom and it was apparent that a similar parameter value was appropriate for the lower area (this may be an artefact of the original model setup and there are no data to really assess this).

Q92F

This catchment is a tributary to the Konnap River and was previously studied intensively by the IWR during the 1990s. The simulated recharge of 1% agrees reasonably well with detailed field study data and lies between the RECHP and MEAN_KS estimates. The T value in the GRAII database was considered to be far too high (41.8) for this region and was reduced to 5.0 $m^2\ d^{-1}$. This is a situation where the channel loss parameter (TLGMax) becomes important as the near channel slope element gradient is negative for 40% of the time. A potentially important consequence of the model results is that for 60% of the time the groundwater is moving toward the channel but not contributing to streamflow. However, the groundwater movement is almost certainly maintaining channel pool storage and the impact of groundwater abstractions under such situations has the potential to affect the ecological functioning of semi-arid rivers of this type (Hughes, 2005). The simulation results are broadly consistent with what is known about the real hydrological response of this catchment.

Q94A and Q94F

These represent two catchments in the Kat River (tributary to the Great Fish River in the Eastern Cape). The headwaters (A) are steep and rocky, while the lower catchment (F) is in a much drier area with lower slopes. The simulated recharge values are broadly similar to the MEAN_KS values in the GRAII database and higher values of GW would not produce such good results (log CE values of 0.926 and 0.941), unless the riparian strip factor parameter was also increased to reduce the groundwater discharge. Channel transmission losses play a significant role in the lower catchment, while the groundwater is almost always effluent within Q94A. The results are intuitively reasonable.

V60A, V60D and V60F

These catchments are located within the Sundays River catchment, a tributary of the Thukela River. Simulated recharge values are close to or less than the MEAN_KS values (the lowest estimates in the GRAII database) and all the log CE values are close to 0.92. The best results were obtained by reducing FT slightly and with relatively high riparian strip factors (0.4%). The model simulates groundwater as always effluent.

X31A

This is one of the headwater tributaries of the Sabie River, which has steep slopes and some parts of the catchment underlain by dolomites. The simulated recharge is between RECHP and MEAN_KS, but closer to MEAN_KS. A large proportion of the recharge emerges as contributions to streamflow, but the model suggests that interflow is the dominant runoff generation process.

4.4 Assessment of Calibration Tests

In general, the modified Pitman model was able to replicate hydrographs produced using the original Pitman model while taking into account groundwater factors. Some problems were encountered in dolomitic catchments, but these are thought to be a result of the modelling approach used by WR90, and not the result of problems with the modified Pitman model. The following general observations can be made:

- Where the original Pitman model was used with a non-zero value of the original GW parameter and the groundwater delay function (GL), the new version of the model is not able to reproduce the simulated WR90 baseflow response. This issue needs to be investigated further.

- In the majority of catchments investigated the simulated mean annual recharge was closer to the MEAN_KS values in the GRAII database (with E10 a notable exception).
- If the recharge is increased (to match the RECHP estimates), in some catchments a similar result can be achieved by adjustments to other parameters (RSF, for example), while in others the correspondence with the WR90 simulated data deteriorates.
- As a consequence of the previous point it is essential to further develop guidelines for setting the riparian strip factor parameter based on an understanding of near-channel groundwater processes.
- A similar point could be made about the drainage density parameter. Further guidelines are required to establish acceptable *a priori* values for this parameter.
- There are some catchments where the GRAII database values for T were changed to better reflect the intuitive assessment of transmissivity of the authors of this document.

5 GUIDELINES FOR ESTIMATING GROUNDWATER PARAMETERS FOR THE REVISED PITMAN MODEL

5.1 Preamble

The basis of these guidelines is to achieve closely similar time series of total monthly flow volumes for the 70 year period (1920-1990) as provided in WR90. The assumption is that the same input rainfall and evaporation data will be used and that, except where specified, the original parameters of the model that have not changed their meaning will have the same values as those recommended in WR90.

These are therefore not guidelines for calibrating the model against observed flows, which represents a different issue and is not addressed in this report.

It was decided that the main source for quantifying many of the parameter values should be the GRAII database of groundwater information for all the quaternary catchments in the country.

5.2 Maximum Recharge Rate (mm/month) GW

The original version of the model simulated all baseflow using one function (parameters FT and POW), the ‘groundwater’ component then being a proportion of the total and routed more slowly. The revised version has two functions, the original (retaining the function based on FT and POW, but with all the simulated flow treated as interflow) and a new function of the same form but with different parameters (GW and GPOW) to represent recharge. It is very difficult to directly estimate the value of the maximum monthly recharge rate and therefore the recommended procedure is to start with an approximate estimate and then to adjust (calibrate) the GW parameter to achieve a mean annual recharge value that is acceptable. Three such estimates are provided in GRAII and there are no clear guidelines as to which is likely to be the best estimate. Limited experience suggests a value somewhere between the lowest and middle estimates are the most realistic.

In adjusting the GW parameter it is sometimes necessary to similarly adjust the FT parameter as these are both draining the main model moisture storage. FT is therefore the only parameter that may require a different value to the WR90 recommended value in the new version of the model. The basis for the adjustment is to ensure that the pattern of low flow response is similar to the pattern in the WR90 simulated flows.

5.3 Power : Storage-Recharge Curve GPOW

While there are indications that this parameter can be quantified to reflect the variations in recharge response with changes in near surface moisture content, there are no sources of information currently available and it is recommended that a value of 3.0 is used.

5.4 Drainage Density

The drainage density parameter represents the total length of channels per km^2 of the catchment area that is expected to experience groundwater flow to the channel. It is not therefore the total drainage density of the catchment. There are no clear guidelines for estimating this parameter, but for relatively humid catchments with continuous groundwater contributions to streamflow, a default value of 0.4 is recommended, while for more arid catchments the density can be decreased to 0.2 or less. The drainage density parameter determines the conceptual geometry of the groundwater aquifer beneath the catchment and low densities will slow down the outflow from the groundwater making the response less variable.

5.5 Transmissivity (m^2/day) T

Default values can be taken directly from the GRAII database. However, it should be noted that the transmissivity parameter in the model represents an average value for the catchment rather than a value that might be measured in the vicinity of boreholes. It has already been noted that there are some apparently anomalous values in the GRAII database, and it is recommended transmissivity values are checked against other values for catchments assumed to have similar geology. Testing of the model suggested the using a T value of half that in the GRAII database yields reasonable results.

5.6 Storativity

The default values for storativity can also be taken directly from the GRAII database. The most important effect of changing the storativity is its effect on the variability of the groundwater discharge to the channel. Lower values imply less storage and therefore a faster response to any given recharge input.

5.7 Regional Groundwater Drainage Slope

There are values given in the GRAII database, but these are generally based on information that is not the same as used in the model. A value of 0.01 is generally suitable and this parameter has a relatively minor impact on the simulation results unless it is made very large (i.e. greater than about 0.05).

5.8 Rest Groundwater Level (m below surface)

This is also generally not a very important parameter and there are values given in the GRAII database. It can become important if the abstraction routines are used as it determines the maximum level of drawdown.

5.9 Riparian Strip Factor (% slope width)

This is a relatively important parameter as it determines the amount of groundwater that can be lost to evaporation in the near-channel margins. It is very difficult to develop clear guidelines for estimating this parameter value as its effect on the simulated results depends upon many other factors such as the recharge and the frequency with which the conceptual groundwater gradients are positive (and therefore generating discharge to channel flow). It is therefore suggested that a default value of 0.2% be used except where there are good reasons to increase or decrease the value. An increase to 0.4 or 0.5% would be justified when it is known that riparian vegetation plays a major role in affecting the water balance of the near channel environment.

If the recharge is not sufficient to generate continuous groundwater discharge to the channel (i.e. always positive near-channel groundwater gradients), the amount of evaporation from the channel margins may also affect the channel loss function. If the objective of setting parameter values in a specific quaternary catchment is to generate channel losses (from runoff generated upstream), then the results may be quite sensitive to the value of this parameter. Unfortunately, there is almost no available data that can be used to properly assess the channel loss function in the model (see next section).

5.10 Channel Loss - TLGMax (mm)

The channel loss function relies upon two highly conceptualized functions and the single parameter TLGMax. This parameter is used to quantify the maximum channel loss from incremental runoff (i.e. runoff generated within the tributaries of a quaternary catchment), as well as from channel flow passing through a quaternary catchment (i.e. runoff generated from upstream). The first function relates losses to the groundwater gradient (more negative gradients imply greater potential for loss), while the second relates losses to the maximum generated flow (incremental or upstream). The parameter TLGMax (mm) represents the maximum loss from incremental flow, while a new value is created automatically for the maximum loss from upstream flows.

If maxqs = maximum incremental runoff (mm) and maxqc = maximum total runoff from the quaternary ($m^3 * 10^6$) then the maximum loss from upstream channel flow is:

$$\mathbf{TLGMax_{upstream} = TLGMax * maxqs / maxqc} \qquad \mathbf{(21)}$$

The maximum loss (TLGMax for incremental runoff) occurs when the generated runoff is at a maximum for the whole simulated time series. Given that the groundwater gradient is very negative (i.e. groundwater level well below the channel), the minimum channel loss will be 0.2 *

TLGMax. This means that runoff less than 20% of the maximum loss parameter values will be completely lost to channel transmission losses. If the groundwater gradients are less negative the losses will be reduced.

An example can be used to illustrate the operation of the function. Assume that the quaternary being modelled has a maximum incremental simulated runoff of 10 mm and that the maximum downstream outflow is 6 $*10^6$ m^3. If the maximum loss parameter is set at 2 mm, then incremental losses will vary between 0.4 and 2 mm, while upstream losses will vary between 0.24 and 1.2 $*10^6$ m^3 (when the groundwater gradients are very negative).

As already indicated, there are very few available data that can be used to suggest whether the format of this channel loss function is adequate, nor to quantify the parameter value. Further work is required to determine suitable parameter values for the different parts of the country. In the meantime the best approach is to experiment with different parameter values (start with 0 for the no loss situation) until an intuitively sensible pattern of loss values is achieved.

6 CONCLUSIONS AND RECOMMENDATIONS

The well-known rainfall-runoff Pitman model was modified during the research project to take account of groundwater. Using national scale parameters pertaining to recharge, transmissivity, storativity and slope, the model can be used to estimate the contribution of groundwater to baseflow. The modified model can be used to identify those areas in which groundwater plays an important role in sustaining baseflow, thus allowing for the optimisation of the allocation of human and financial resources for Reserve determinations. As a first approximation, Figure 1 can be used to assess the probability of groundwater contributing to baseflow.

Testing of the modified Pitman model in 17 quaternary catchments showed that it is capable of replicating hydrographs produced using the original Pitman model, while at the same time providing intuitively correct assessment of surface - groundwater interactions. Some catchment specific problems were encountered, but these are thought to be a consequence of the original modelling of the catchment rather than problems with the modified Pitman model.

It was not possible during the course of the research project to develop management tools to ensure that the groundwater contribution to baseflow is not impacted by abstraction. As the modified Pitman model operates on a quaternary catchment basis, it would be difficult to apply the model to site-specific conditions.

Incorporation of the modified Pitman model into the SPATSIM software provides hydrologists with a useful tool to quantify surface - groundwater interaction at a catchment scale. Proper training in the use of the software is required to yield reliable results. It is therefore proposed that training courses be held to obtain the greatest benefit from this research programme.

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