WATER RESOURCES OF SOUTH AFRICA, 2012 STUDY (WR2012)

Volume 8: WRSM/Pitman Theory Manual

AK Bailey & WV Pitman

TT 690/16

WATER RESOURCES OF SOUTH AFRICA, 2012 STUDY (WR2012)

WRSM/Pitman Theory Manual

Report to the
Water Research Commission

by

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Royal HaskoningDHV (Pty) Ltd

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1. WR2012 Executive Summary (WRC Report No. TT 683/16)
2. WR2012 User Guide (WRC Report No. TT 684/16)
3. WR2012 Book of Maps (WRC Report No. TT 685/16)
4. WR2012 Calibration Accuracy (WRC Report No TT 686/16)
5. WR2012 SAMI Groundwater module: Verification Studies, Default Parameters and Calibration Guide (WRC Report No. TT 687/16)
6. WR2012 SALMOD: Salinity Modelling of the Upper Vaal, Middle Vaal and Lower Vaal sub-Water Management Areas (new Vaal Water Management Area) (WRC Report No. TT 688/16)
7. WRSM/Pitman User Manual (WRC Report No. TT 689/16)
8. **WRSM/Pitman Theory Manual (WRC Report No. TT 690/16 – this report)**
9. WRSM/Pitman Programmer's Code Manual WRC Report No. TT 691/16)

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Royal HaskoningDHV DISCLAIMER ON WRSM/PITMAN*

Although every possible care has been taken in writing the software program WRSM/Pitman*, its operation is open to intentional and unintentional misuse and the results that it produces are open to misinterpretation.

For this reason there cannot be any guarantee whatsoever about the correctness of the results produced by the program. TiSD, the authors and supporters (WRC and DWS) of WRSM/Pitman will therefore not take any responsibility whatsoever for damages, whatever their nature, resulting either directly or indirectly from the use of the program.

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1 RUNOFF MODULE (PRIOR TO 2005 ENHANCEMENTS)

1.1 Introduction

The theory underlying the runoff module was first described in Hydrological Research Unit (HRU) Report No. 2/73 “A Mathematical Model for Generating Monthly River Flows from Meteorological Data in South Africa”, published in 1973. Since that time a few minor changes have been made to the model – these changes are reported here in what is an abbreviated description of the model. Recent changes to the model structure to accommodate groundwater are described in a separate section.

1.2 Precipitation

Although the model is designed to handle input data to one-month time resolution, provision is made to solve the water balance of the catchment at smaller time intervals. In the original model the number of time steps per month was an input variable, NIT, but NIT was subsequently fixed at a value of 4. Much valuable information on temporal distribution of rainfall is lost if the monthly total is proportioned equally into each such time interval. Accordingly, a disaggregation procedure was adopted to reflect the deviation of actual rainfall rates from the monthly average, as described below.
Let

P = total precipitation for a month (mm)

And

W = maximum deviation of cumulative rainfall above and below the line representing the average rate (mm)

Then

$$W = -2 + 1.3732(P + 1.6)^{0.8} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (1.1)$$

This equation was derived from an analysis of several daily rainfall records and is a best-fit to the data from all the stations. It also satisfies the requirement that W = P for very small falls associated with a single daily event and that W becomes a progressively smaller percentage of P as P increases (see Figure 1.1).
Once the value of W has been calculated for a given month the cumulative rainfall curve is synthesized by the following equation, which describes an S-shaped curve (see Figure 1.2).

$$y = x^n / (x^n + (1 - x)^n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.2)$$

Where

Y = cumulative precipitation / total precipitation
x = cumulative time / total time
n = exponent related to W

The relationship between n and W within the range of likely values of P is given by the following equation:

$$N = 1.28 / (1.02 - W / P)^{1.49} \quad \text{.........................}(1.3)$$

1.3 Catchment rainfall

Catchment rainfall, which is a fundamental input to the runoff, irrigation, reservoir and channel modules, is derived by "averaging" the rainfall records of a number of individual stations. The method of averaging – as described below – is designed to avoid bias, especially when dealing with mountainous catchments where isohyetal gradients are steep. For each month for which catchment rainfall is required, let:

P_n = Monthly precipitation for rain gauge no. "n".
M_n = Mean annual precipitation (MAP) for rain gauge no. "n"
N = Total no. of rain gauges used in the averaging process.
PC = Catchment rainfall expressed as a percentage of its MAP

$$PC = 100 \times [(P_n / M_n)] / N \quad \text{.........................}(1.4)$$

The method gives equal weight to all stations used, but has the advantage that individual station records can vary, provided there is at least one record available at all times. The output, in the form of monthly rainfall percentals, is converted to millimetres in the model by application of the appropriate MAP.

1.4 Interception

To estimate the total interception losses over a month, the following assumptions were made:

- the total rainfall on any rain-day results from one event only and
- the water held in interception storage has time to evaporate completely between successive rain-days.

With these assumptions in mind it was possible to derive monthly interception losses for a number of daily rainfall records. The best-fit curves of interception loss versus monthly rainfall took the following form:

$$I = a(1 - e^{bP}) \quad \text{.........................}(1.5)$$

Where

I = total interception for the month;
P = total precipitation for the month and
a, b = constants

For the range of interception storages to be applicable (0 – 10 mm), the empirical relationships between a, b and PI (interception storage) were found to be:

$$a = 13.08\ \mathrm{PI}^{1.14} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.6)$$

and

$$b = 0.00099\ \mathrm{PI}^{0.75} - 0.011 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.7)$$

Figure 1.3 shows the relationship between interception loss and monthly rainfall for interception storages of 4 and 8 mm.

1.5 Surface runoff

Surface runoff is taken to be derived from two components, namely:

- runoff from impervious areas and
- runoff resulting from rainfall not absorbed by the soil.

The first component is easily computed by multiplying catchment rainfall by the area of catchment that is impervious. In the original model the impervious fraction (AI) was fixed, but this has been amended so that a time-varying AI can be entered to reflect the growth of urbanized areas.

In computing runoff from the second component it is assumed that absorption or infiltration varies across the catchment from a minimum rate to a maximum rate, with a symmetrical, triangular frequency distribution across the catchment (see Figure 1.4). The only variables needed to describe such a distribution of absorption rate are as follows:

Zmin = minimum absorption rate (mm/month)
Zmax = maximum absorption rate (mm/month)
Zave = mean absorption rate (mm/month) $= (\mathrm{Zmin} + \mathrm{Zmax})/2$ …….(1.8)

Derivation of the equations for surface runoff is given in the original HRU Report No. 2/73; only the final equations are presented here.

Let

r = rainfall (mm)

and

Surf = surface runoff (mm)

Case 1:

$$r < \mathrm{Zmin} \qquad \mathrm{Surf} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.9)$$

Case 2:

$$\mathrm{Zmin} < r < \mathrm{Zave} \qquad \mathrm{Surf} = 2(r\ \mathrm{Zmin})^3 / 3(\mathrm{Zmax} - \mathrm{Zmin})^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1.10)$$

Case 3:

$\mathrm{Zave} < \mathrm{r} < \mathrm{Zmax} \qquad \mathrm{Surf} = \mathrm{r} - \mathrm{Zave} + 2(\mathrm{Zmax} - \mathrm{r})^3 / 3(\mathrm{Zmax} - \mathrm{Zmin})2$ ....(1.11)

Case 4:

$\mathrm{r} > \mathrm{Zmax} \qquad \mathrm{Surf} = \mathrm{r} - \mathrm{Zave}$ ....(1.12)

1.6 Sub-surface runoff

Sub-surface runoff (Q in mm) is directly related to soil moisture according to the following equation, which is shown in graphical form in Figure 1.5:

$\mathrm{Q} \quad = \quad \mathrm{FT}[(\mathrm{S} - \mathrm{SL}) / (\mathrm{ST} - \mathrm{SL})]\mathrm{POW}$ ....(1.13)

Where

SL = soil moisture below which no runoff occurs (mm)
ST = total soil moisture capacity (mm)
FT = runoff at soil moisture equal to ST (mm)
S = actual soil moisture status (mm)
POW = power of Q – S curve

An additional parameter GW (maximum baseflow rate) is necessary in cases where the time lags of the different runoff components vary significantly. If the soil moisture is such that Q is less than GW the associated runoff is considered to be all baseflow and is lagged accordingly. If the storage is such that Q is greater than GW the remainder (Q – GW) is lagged to a much smaller degree than the baseflow component. A description of the lagging procedure follows.

1.7 Time delay of runoff

Lagging of runoff to the catchment outlet is achieved by application of the Muskingum equation with the weighting factor (x) set to zero for reservoir-type routing, as follows:

$\mathrm{O}_2 \quad = \quad \mathrm{O}_1 + \mathrm{C}_1(\mathrm{I}_1 - \mathrm{O}_1) - \mathrm{C}_2(\mathrm{I}_2 - \mathrm{I}_1)$ ....(1.14)

Where

$\mathrm{C}_1 \quad = \quad \Delta\mathrm{t} / (\mathrm{k} + 0.5\Delta\mathrm{t})$ ....(1.15)

and

$\mathrm{C}_2 \quad = \quad 0.5\Delta\mathrm{t} / (\mathrm{k} + 0.5\Delta\mathrm{t})$ ....(1.16)

In the context of this model the variables are given the following interpretation:

O = monthly runoff at catchment outlet (mm)
I = instantaneous monthly runoff (mm)
Δt = routing period (normally one month)
K = lag of runoff (months)

Subscripts $_1$ and $_2$ to I and O refer to the previous and current month's runoffs respectively. In the model allowance is made to lag two components of runoff by assigning different 'k' values. All runoff from soil moisture that is equal to or less than GW is assigned a 'k' value equal to GL and all remaining runoff is assigned a somewhat shorter lag with $k = TL$ *(i.e. TL << GL).*

1.8 Evaporation from soil moisture

Catchment evapotranspiration, E, is assumed to be equal to potential evaporation, PE, when soil moisture, S, is at full capacity, ST. The relationship between E and S is assumed to be linear with a minimum S at which e is equal to zero. The slopes of the E–S lines are assumed to lie between two limits, as defined by the variable 'R' that ranges between 0 and 1. When R = 0 the relationship E/PE = S/ST applies and when R = 1 the slopes of the E–S lines are all the same and equal to PEMAX/ST, where PEMAX is the maximum monthly potential evaporation (see Figure 1.6). Derivation of the E–S equation is given in HRU Report No. 2/73 – only the final equation is presented here.

$$E = bS + c \quad \text{……………………………………………………………………………(1.17)}$$

Where

$$b = PE / [ST(1 - R(1 - PE / PEMAX))] \quad \text{…………………………………………(1.18)}$$

and

$$c = PE - PE / [1 - R(1 - PE / PEMAX)] \quad \text{……………………………………(1.19)}$$

1.9 Calculation procedure

The calculation procedure for each month follows the following steps:

- Compute runoff from impervious area;
- Determine interception loss;
- Synthesize mass curve of rainfall for the month and calculate rainfall for each time step;
- The following 9 steps are performed for each time step;
- Subtract interception loss from rainfall;
- Compute surface runoff;
- Perform mass balance of soil moisture to determine soil moisture at end of time interval. Note that evaporation from soil moisture is adjusted to account for the evaporative loss from intercepted rainfall;

- If soil moisture capacity is exceeded calculate the excess water (SPILL) and apportion it to baseflow (to be lagged by GW) and remaining flow (lag of TL) as per step 9;
- The quantity SPILL × GW/FT is added to baseflow and the remainder is added to the component to be lagged by TL. (Note that this procedure is different to that of the original model in which all of the SPILL is added to the component lagged by TL.);
- Compute the runoff components originating from soil moisture;
- Accumulate runoff components for the month;
- After all months have been processed perform the routing (lagging) procedure and combine runoff components to obtain total monthly runoffs and
- Convert monthly runoffs from depths (mm) to volumes (million cubic metres).

1.10 Figures

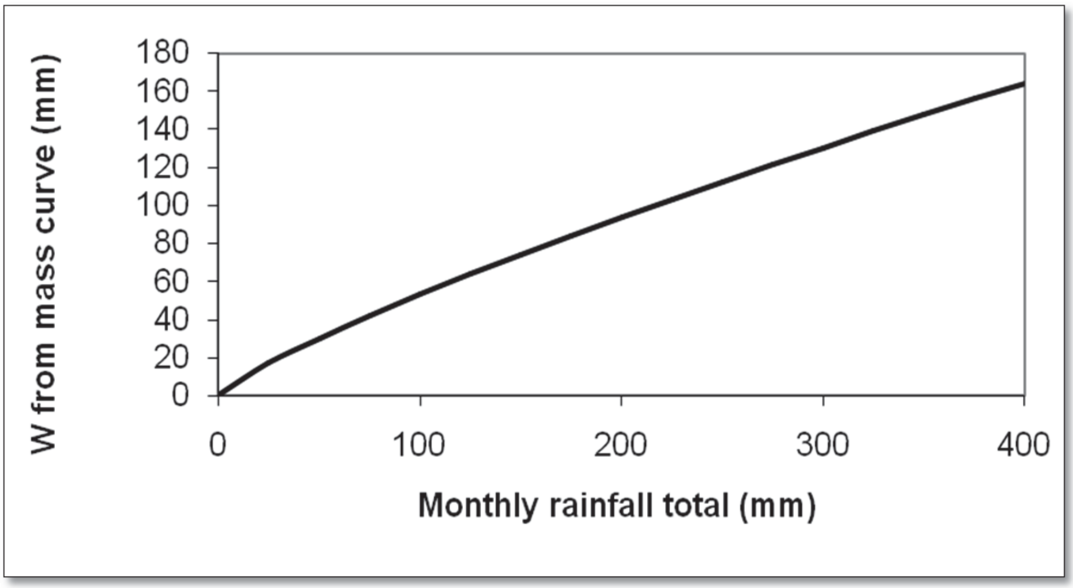


Figure 1.1: **Mean relationship between W from mass curve and monthly rainfall**

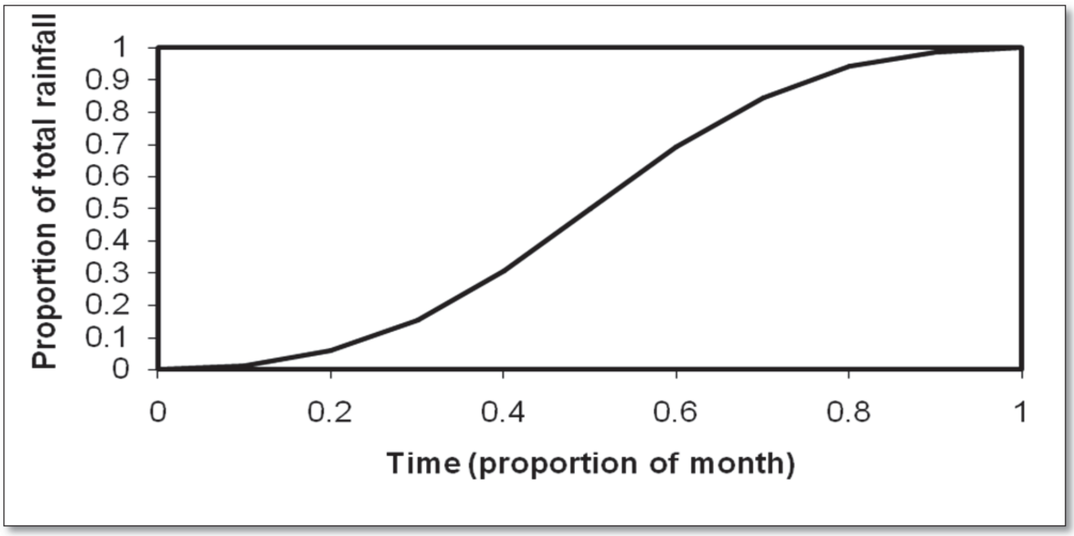


Figure 1.2: Synthesized Mass Curve of Monthly Rainfall

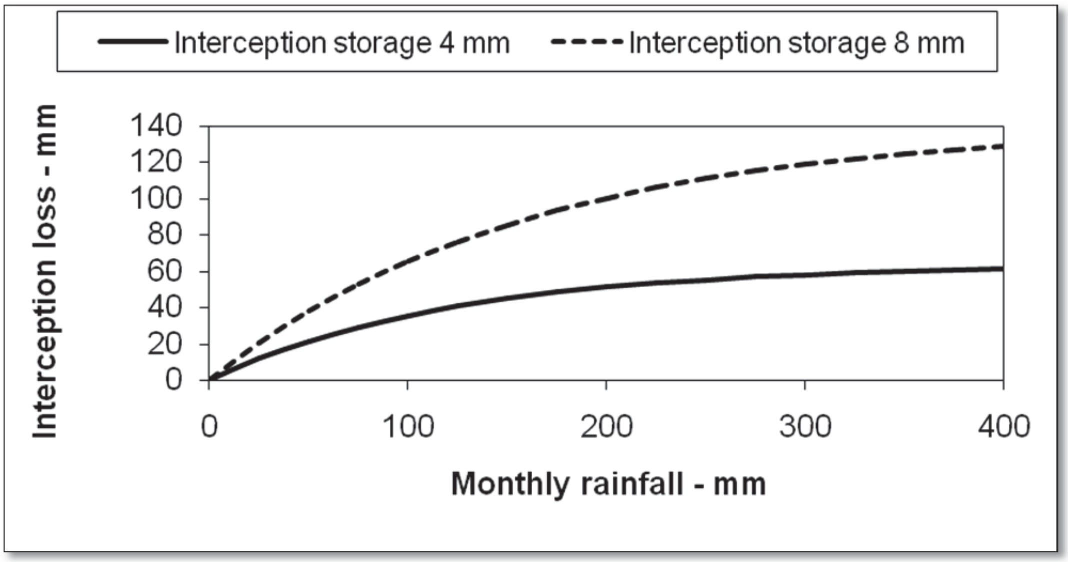


Figure 1.3: Monthly Interception Loss

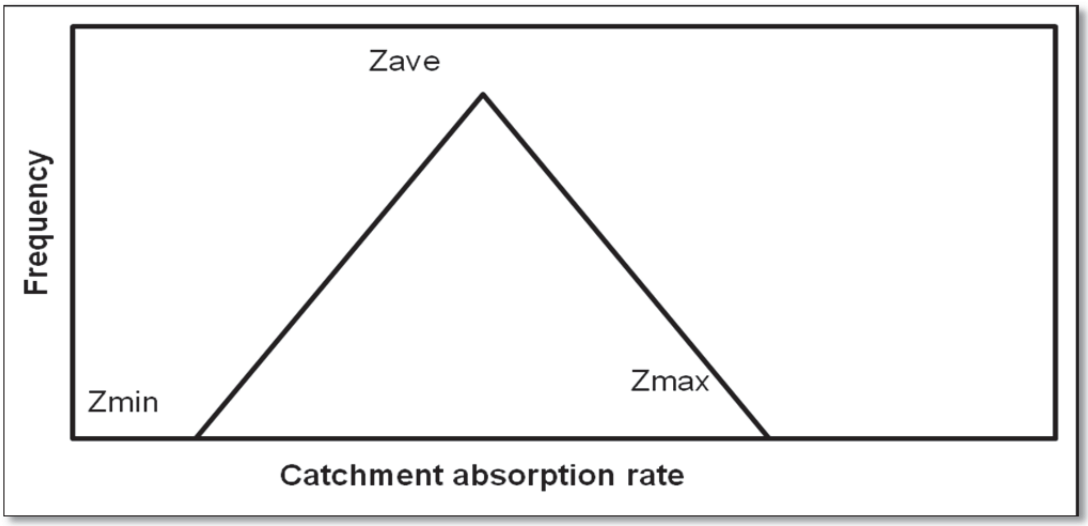


Figure 1.4: Frequency Distribution of Catchment Absorption Rate

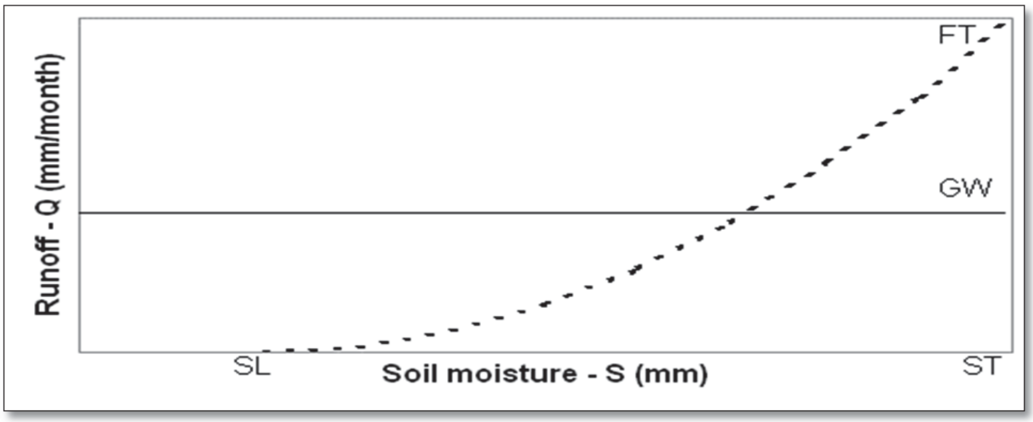


Figure 1.5: Soil Moisture – Runoff Relationship

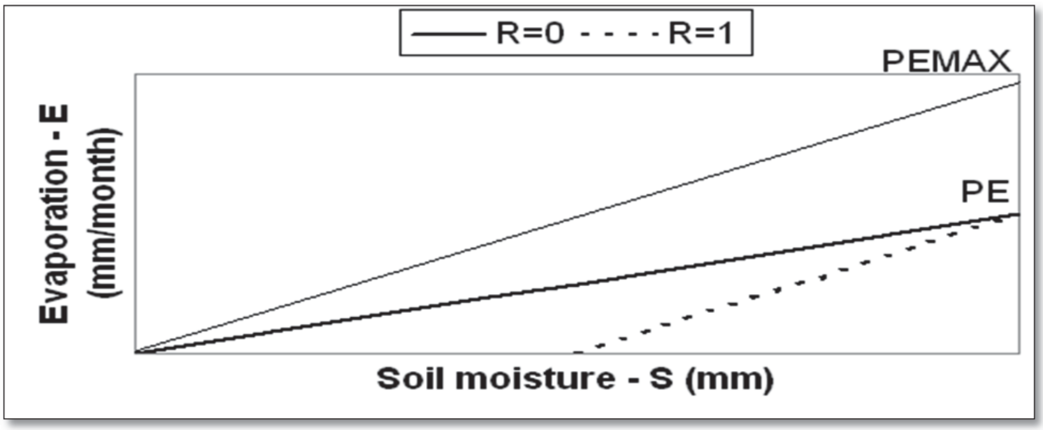


Figure 1.6: Evaporation – Soil Moisture Relationships

2 RESERVOIR MODULE (UNCHANGED FROM WR2005 TO WR2012 STUDIES)

2.1 Mass balance

The reservoir module performs a simple mass balance for each month, taking into account all inflows, outflows (including evaporation and spillage) and changes in storage state, as described below. All volumes are in million cubic metres and the reservoir surface area is in square km.

Let

S = storage state
CAP = (live) reservoir capacity
A = reservoir surface area
FSA = full supply area
I = total inflow
D = total draft (i.e. controlled releases)
P = precipitation on reservoir surface (mm)
G = average gross evaporation (mm)
E = net evaporation loss from reservoir
$SPILL$ = uncontrolled spillage from the reservoir

Subscripts $_1$ and $_2$ to variables S and A refer to the beginning and end of the month respectively.
Net evaporation loss is calculated, based on the area at the start of the month, as follows:

$$E = A_1 \times (G - P) / 1000 \quad \ldots\ldots\ldots\ldots\ldots\ldots(2.1)$$

The mass balance is first done assuming the dam neither dries up nor spills, as follows:

$$S_2 = S_1 + I - D - E \quad \ldots\ldots\ldots\ldots\ldots\ldots(2.2)$$

The preliminary month-end value of S is then compared with the capacity, CAP, to determine the spillage for the month, SPILL.

If $S_2 < CAP$: $SPILL = 0$
If $S_2 > CAP$: $SPILL\ S_2 - CAP$ and $S2 = CAP$

The next test is to check if the preliminary month-end value of S is less than zero, to determine whether the full draft D can be supplied, otherwise D is reduced as follows:

If $S_2 < 0$: $D = D + S_2$ and $S_2 = 0$

2.2 Area – storage relationship

The water balance keeps a continual track of the reservoir storage state S. The area for a given storage is calculated by the following equation:

$$A = a \times S^{b} \quad \text{.......................................} (2.3)$$

The constant "b" is determined from the area-capacity tables of the reservoir to be modelled, however, if such information is unavailable a value of "b" equal to 0.6 is assumed. (A "b" of 0.6 represents the average for all reservoirs in South Africa.) The value of "a" is calculated by putting A = FSA and S = CAP into the above equation.

2.3 Controlled releases or draft – D

Controlled releases can be withdrawals from the reservoir or compensation releases downstream. There are three types of release/draft, namely:

- Supplies to an irrigation module, which are first calculated by that module;
- A time series of demands, covering the period to be simulated or
- A set of 12 demands, one for each calendar month, with the option of reducing demand when the storage state S falls below a prescribed level.

Option 3 requires a "trigger level" of storage, below which the demands are reduced, and a reduction factor that is applied to the demand. The calculation is set out below.

Let

D_m = demand for the month
Sr = trigger level of storage below which demand is released
Fr = reduction factor to be applied to demand

Then

If $S > Sr$: $D = D_m$ ....(2.4)
If $S < Sr$: $D = Fr \times D_m$ ....(2.5)

3 IRRIGATION MODULE (PRIOR TO WR2005 STUDY ENHANCEMENTS)

The irrigation module is not meant to be used to design an irrigation layout but merely to estimate the effect of upstream irrigation usage on downstream river flow. The calculation of irrigation usage is based on the following variables:

Airrig = Total area under irrigation (km^2), which can change from year to year
Pindex = Proportion of total area under irrigation in each calendar month
Apan = Mean monthly A-pan evaporations for each calendar month (mm)
Cropf = Crop factors for each calendar month (depend on crops grown)
Reff = Effective rainfall factors for each calendar month
P = Actual rainfall for the month (mm)
Ret = Return flow as percentage of application

The calculations proceed (for each month) as follows:

Gross demand (mm): $G = \text{Apan} \times \text{Cropf}$ ……………………………………………………………(3.1)
Net demand (mm): $N = \text{MAX}\,(G - P \times \text{Reff}, 0)$ (to avoid negative values) ……….(3.2)

Volumetric demand (million cubic metres):

$V = 0.001 \times N \times \text{Airrig} \times \text{Pindex}$ ………………………………………………….(3.3)

Return flow from the irrigation area (million cubic metres):

$RF = 0.01 \times \text{Ret} \times V$ …………………………………………………………………….(3.4)

The calculations do not specifically allow for irrigation efficiency, as much of the “wasted” water will find its way back to the river. However, one can increase the total irrigation area to cater for inefficiencies – implying that water is wasted by “irrigating” areas outside those under crops.

4 IRRIGATION (WITH WR2005 STUDY ENHANCEMENTS) BY DR CE HEROLD

4.1 WQT Type 2 Algorithm

Irrigation Block Model

An irrigation block sub-model has been developed which accounts for the continuity of mass for salt and allows further accumulation and flushing of salt from the irrigated lands. The irrigation sub-model structure is illustrated in Figure 4.1

4.1.1 Water Mass Balance

The monthly unit irrigation demand (before allowances for losses) DIN (mm) is given as:

$$\mathrm{DIN} = \sum_{\substack{\mathrm{i}=1 \\ \text{positive value only}}}^{\mathrm{NCROPS}} \left|\mathrm{CPF_i} \times (\mathrm{PE_m} \times \mathrm{CF_{im}} - \mathrm{ER_m})/100\right| \ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

Where:

NCROPS = total number of crops planted

M = month of the year

$\mathrm{PE_m}$ = potential evaporation for month m (mm)

$\mathrm{CF_m}$ = crop “$_\mathrm{i}$” demand factor for month m

$\mathrm{ER_m}$ = effective rainfall (mm)

$\mathrm{CPF_i}$ = percentage of total irrigated area cultivated using crop “$_\mathrm{i}$”

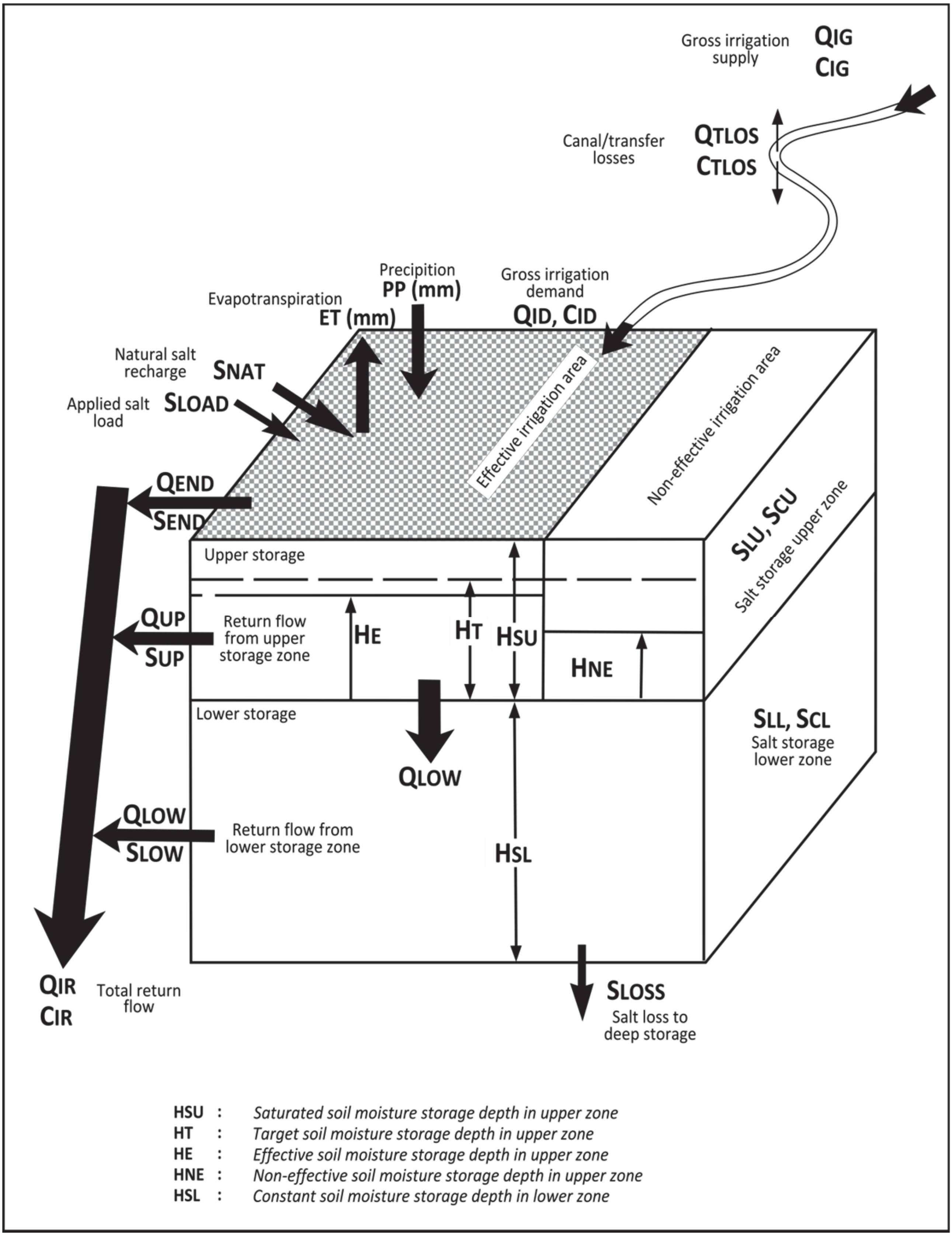


Figure 4.1: Irrigation block sub-model element (from BKS, Vaal River System Analysis)

The effective rainfall is calculated as follows:

$$ER_m = ERF \times RAIN_m \tag{4.2}$$

Where

ERF = effective rainfall factor ($0 < ERF < 1.0$)
$RAIN_m$ = rainfall in month m (mm)

Allowing for the leaching requirements and application losses, the gross irrigation demand is given by:

$$QID = ((DIN \times AEFF) / 1000) \times (100/EFI) \tag{4.3}$$

Where:

QID = gross irrigation demand (10^6 m^3 / month)
AEFF = actual effective irrigated area (km^2)
EFI = irrigation water use efficiency (%)

An allowance is also made for canal/transfer losses in transporting from the raw water source to the irrigated land. Such losses are calculated as follows:

$$QIG = QID + QTLOS \tag{4.4}$$

$$QTLOS = TLPQ \times QIG \tag{4.5}$$

Or

$$QIG = ((DIN \times AEFF) / 1000) \times (100 / EFI) \times (1.0 / (1.0 \quad TLPQ)) \tag{4.6}$$

Where:

QIG = gross irrigation supply required on raw water source (10^6 m^3 / month)
QTLOS = canal/transfer losses in water transport
TLPQ = proportion of canal flow lost in transport

Now if the gross irrigation supply requirement is greater than the available water from the raw water source, then the actual area irrigated during the month is given as follows:

$$AEFF = AREAT \times QAVAIL / QIG \tag{4.7}$$

Where:

AEFF = actual effective irrigated area (km^2)
QAVAIL = available water from raw water source (10^6 m^3 / month)
AREAT = target annual irrigated area (km^2)

Annual gross irrigation supply requirements are also compared with annual irrigation quotas to ensure that the water allocation limit is not violated. If the gross irrigation demand on an annual basis exceeds the annual allocation limit then the irrigated area is adjusted as follows:

$$\text{AREAT} = \text{AREA} \times \text{ALL} / \text{AQIG} \quad (4.8)$$

Where:

AREA = gross irrigated area (km^2)
ALL = annual allocation limit ($10^6\ \text{m}^3$ / annum)
AQIG = annual gross irrigation supply requirements ($10^6\ \text{m}^3$ / annum)

The non-effective irrigation area is the proportion of the gross irrigation area not being irrigated and is given by:

$$\text{ANEFF} = \text{AREA} - \text{AEFF} \quad (4.9)$$

Where:

ANEFF = non-effective irrigated area (km^2)

At the beginning of each month the effective and non-effective irrigation areas are calculated. If the irrigation areas do change, the following calculations are performed to maintain the correct water balance.

```
(a)  If  $\text{AEFF} > \text{RRAE}$
         $\text{DAEFF} = 0$
         $\text{HE} = (\text{HE} \times \text{RRAE} + (\text{AEFF} - \text{RRAE}) \times \text{HNE}) / \text{AEFF}$ ..........(4.10)

     else
         $\text{DAEFF} = \text{RRAE} - \text{AEFF}$ ..........(4.11)

(b)  If  $\text{ANEFF} > \text{RRANE}$
         $\text{DANEFF} = \text{ANEFF} - \text{RRANE}$ ..........(4.12)
         If  $\text{DANEFF} \leq \text{DAEFF}$
             $\text{HNE} = (\text{HNE} \times \text{RRANE} + \text{DANEFF} \times \text{HE}) / \text{ANEFF}$ ..........(4.13)
     else
         $\text{HNE} = (\text{HNE} \times (\text{ANEFF} - \text{DAEFF}) + \text{DAEFF} \times \text{HE}) / \text{ANEFF}$ ..........(4.14)
```

RRAE = Previous time step's effective area (km^2)
RRANE = Previous month's non-effective area (km^2)
DAEFF = Reduction in effective area (km^2)
DANEFF = Increase in non-effective area (km^2)

The soil moisture storage depth is calculated on a monthly basis for both the effective irrigation area and the non-effective irrigation area. The calculation involves the monthly water balance of all water being applied and removed from the different areas.

The water balance equation for the effective and non-effective irrigation area can be stated as follows (note that the water balance equation for the non-effective area is very similar with the irrigation demand omitted):

$\mathrm{HEF} = \mathrm{HES} + \mathrm{DIN} + \mathrm{PP} + \mathrm{ETE} - \mathrm{RE}$ .... (4.15)

$\mathrm{HMEF} = \mathrm{HNES} + \mathrm{PP} - \mathrm{ETNE} - \mathrm{RNE}$ .... (4.16)

Where for the effective area:

HEF = soil moisture storage depth at end of month (mm)
HES = soil moisture storage depth at beginning of month (mm)
DIN = unit irrigation demand (mm)
PP = rainfall on irrigated land (mm)
ETE = evapotranspiration on effective irrigation area (mm)
RE = return flow seepage from effective irrigation area (mm)

Additional parameters used in equation

RRAE = Previous time step's effective area (km^2)
RRANE = Previous month's non-effective area (km^2)
DAEFF = Reduction in effective area (km^2)
DANEFF = Increase in non-effective area (km^2)

The return flow seepage from the effective irrigation area consists of two components, the natural runoff from the catchment as defined by the runoff from the pervious zone in the salt wash-off sub-model and the additional return flow seepage due to the soil moisture storage depth in the effective area of the upper zone. Return flow seepage from the effective area can be calculated as follows:

$\mathrm{RE} = \mathrm{QC} + (\overline{HE}) \times \mathrm{RF}$ .... (4.17)

$\mathrm{QC} = \mathrm{QCAT_p} / \mathrm{ACAT_p} \times 1000$ ....(4.18)

Where:

$\mathrm{QCAT_p}$ = runoff from the pervious zone in the catchment as defined in the associated salt wash – off sub-model (10^6 m^3)
$\mathrm{ACAT_p}$ = previous zone area in catchment (km^2)
QC = unit runoff from previous zone of catchment (mm)
$\overline{HE}$ = the average soil moisture storage depth in the month for effective area
= (HES + HEF) / 2.0
RF = the return flow factor ($0.0 < \mathrm{RF} < 1.0$)

The return flow seepage from the non-effective area is given by the following equation:

RNE = $(\text{QCAT}_p / \text{ACAT}_p) \times 1000 + \overline{HNE} \times \text{RF}$ .... (4.19)

Where:

$\overline{HNE}$ = the average soil moisture storage depth in the month for the non-effective area

= (HNES+HNEF) / 2.0

The evapotranspiration losses from the irrigation area are very difficult to ascertain, but the following relationships are deemed appropriate for our purposes.

For the evapotranspiration losses in the effective irrigation area, if the average solid moisture storage depth is less than the target soil moisture depth the following equation holds:

ETE = $(\text{TCD} / \text{HT}) \times \overline{HE}$ .... (4.20)

Where:

ETE = evapotranspiration (mm) in the effective area

TCD = total crop water demands (mm) which is equal to the sum of the potential evaporation times the crop demand factor for all crops

HT = the target soil moisture storage depth (mm)

If the average soil moisture storage depth is greater than the target soil moisture storage depth, then two possibilities exist.

If the potential lake evaporation, PEL is greater than the total crop water demands, the following equation holds:

ETE = $\text{TCD} + (\overline{HE} - \text{HT}) / (\text{HSU} - \text{HT}) (\text{PEL} - \text{TCD})$ .... (4.21)

If not then:

ETE = TCD .... (4.22)

Where:

HSU = the saturated soil moisture depth in the upper zone (mm)

For the evapotranspiration losses in the non-effective irrigation area, the following equation holds:

ETNE $(\text{PEL} / \text{HSU}) \times \text{HNE}$ .... (4.23)

The relationship between evapotranspiration in the irrigation area with the soil moisture storage depth is illustrated in the following chart.

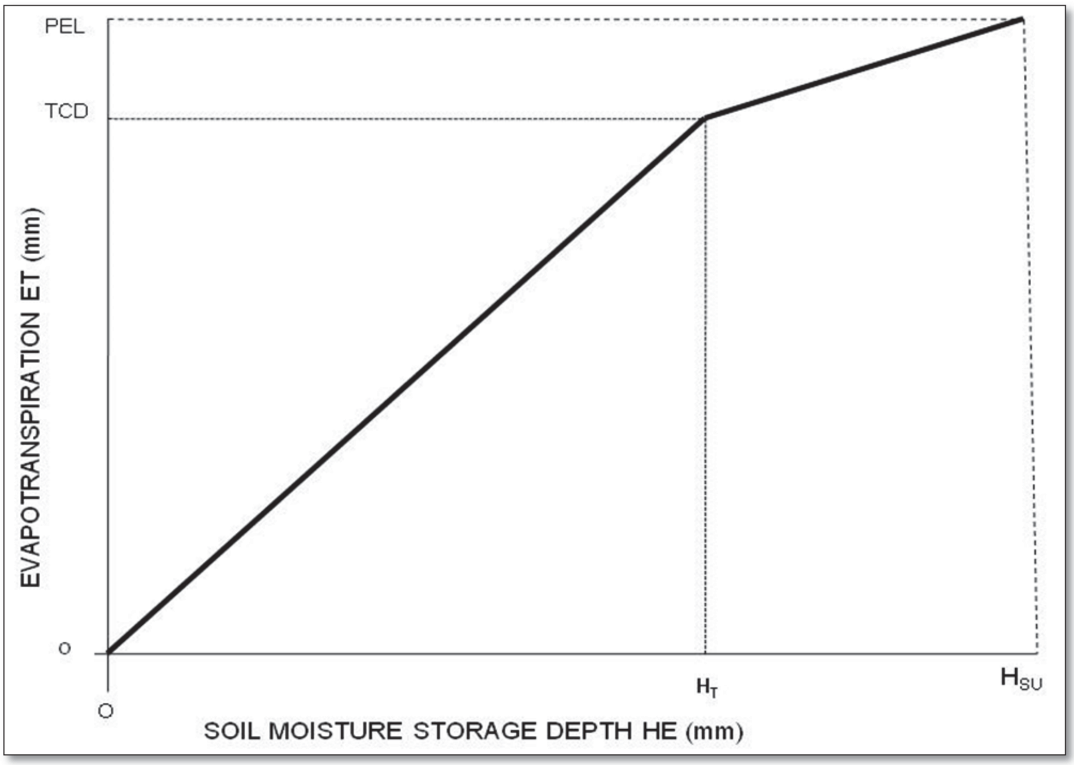


Figure 4.2: Soil moisture storage depth HE (mm)

Using the water balance equations (4.15 and 4.16) and the appropriate component equation (4.17 to 4.23), the final soil moisture storage depth for the effective and non-effective areas can be calculated.
For the effective irrigation area:

(a) $\overline{HE} < \mathrm{HT}$

$$\mathrm{HEF} = (\mathrm{HES} \times (1.0 - \mathrm{TCD} / \mathrm{HT} / 2.0 + \mathrm{RF} / 2.0) + \mathrm{PP} + \mathrm{DIN} - \mathrm{QC}) / (1.0 + \mathrm{TCD} / \mathrm{HT} / 2.0 + \mathrm{RF} / 2.0) \quad (4.24)$$

(b) $\overline{HE} < \mathrm{HT}$ $\quad$ $\mathrm{PEL} > \mathrm{TCD}$

$$\mathrm{HEF} = (\mathrm{HES} \times (1.0 - \mathrm{RF}/ 2.0) + \mathrm{PP} + \mathrm{DIN} - \mathrm{QC} - \mathrm{TCD} + \mathrm{FACT} \times (\mathrm{HT} - \mathrm{HEP} / 2.0)) / (1.0 + \mathrm{RF} / 2.0 + \mathrm{FACT} / 2.0)$$

$$\mathrm{FACT} = (\mathrm{PEL} - \mathrm{TCD}) / (\mathrm{HSU} - \mathrm{HT}) \quad (4.25)$$

(c) $\overline{HE} > \mathrm{HT}$ $\quad$ $\mathrm{PEL} < \mathrm{TCD}$

$$\mathrm{HEF} = (\mathrm{HES} \times (1.0 - \mathrm{RF} / 2.0) + \mathrm{PP} + \mathrm{DIN} - \mathrm{QC} - \mathrm{TCD}) / (1.0 + \mathrm{RF}/2.0) \quad (4.26)$$

For the non-effective irrigation area

$$\mathrm{HNEF} = (\mathrm{HNES} \times (1.0 - \mathrm{PEL} / \mathrm{HSU} / 2.0 - \mathrm{RF} / 2.0) + \mathrm{PP} - \mathrm{QC}) / (1.0 + \mathrm{PEL} / \mathrm{HSU} / 2.0 + \mathrm{RF} / 2.0) \quad (4.27)$$

If the calculated final soil moisture storage depth is greater than the saturated soil moisture storage depth then the following adjustments are made:

(a) If $\mathrm{HEF} > \mathrm{HSU}$

$$\mathrm{RE} = \mathrm{RE} + (\mathrm{HEF} - \mathrm{HSU})$$
$$\mathrm{HEF} = \mathrm{HSU} \quad (4.28)$$

(b) If $\mathrm{HNEF} > \mathrm{HSU}$

$$\mathrm{REN} = \mathrm{RNE} + (\mathrm{HNEF} - \mathrm{HSU})$$
$$\mathrm{HNEF} = \mathrm{HSU} \quad (4.29)$$

The total return flow volume, RET (10^6 m³), from the irrigation sub-model is calculated as:

$$\mathrm{RET} = (\mathrm{RE} \times \mathrm{AEFF} + \mathrm{RNE} \times \mathrm{ANEFF}) / 1000 \quad (4.30)$$

The total return flow from the irrigation sub-model is assumed to come from three different paths.

(a) surface runoff directly from the area
(b) runoff seepage directly from the upper zone
(c) runoff seepage from the upper zone into the lower zone and then into the stream.
The return flows from each path are calculated as follows:

$$\mathrm{QUP} = \mathrm{RET} \times \mathrm{PRFU}$$
$$\mathrm{QLOW} = \mathrm{RET} \times \mathrm{PRFL}$$
$$\mathrm{QEND} = \mathrm{RET} - \mathrm{QUP} - \mathrm{QLOW} \quad (4.31)$$

Where:

QUP = return flow from upper zone (10^6 m^3)
QLOW = return flow from lower zone (10^6 m^3)
QEND = return flow from surface area (10^6 m^3)
PRFU = proportion of return flow from upper zone
PRFL = proportion of return flow from lower zone

4.2 Salt Mass Balance

The assumption is made in the irrigation block sub-model that complete mixing of salts through the entire scheduled area is achieved. Water losses en-route to the irrigated land via canals and farm dams are assumed to be partly due to evaporation (no salt lost) and partly due to seepage losses outside of the irrigation scheme. Hence, the irrigation salt load lost en-route is calculated as follows:

$$\mathrm{STLOS} = \mathrm{TLPS} \times \mathrm{CIG} \times \mathrm{QIG} \tag{4.32}$$

Where:

STLOS = salt loss in route to the irrigation scheme (tons)
TLPS = proportion of salt load lost en-route
CIG = salt concentration of gross irrigation supply requirements

The sale load reaching the irrigation scheme is given by:

$$\mathrm{SID} = (1.0 - \mathrm{TLPS}) \times \mathrm{CIG} \times \mathrm{QIG} \tag{4.33}$$

$$\mathrm{CID} = \mathrm{SID} / \mathrm{QID} \tag{4.34}$$

Where:

SID = salt load of the gross irrigation demand (tons)
CID = salt concentration of the gross irrigation demand (mg/ℓ)

The net application of salt load to the irrigated area which accounts for fertilizers, gypsum and crop export is calculated as follows:

$$\mathrm{SLOAD} = (\mathrm{SLD} \times \mathrm{AOLD} + \mathrm{SLD}_0 \times \mathrm{ANEW}) \times 100/12 \tag{4.35}$$

Where:

SLOAD = net application salt load (tons)
SLD_0 = application rate for first year under irrigation (t/ha)
SLD = application rate for all subsequent years (t/ha)
AOLD = total irrigation area in year “$_{t-1}$”
ANEW = $\mathrm{AREA}_t - \mathrm{AREA}_{t-1}$ = new irrigation area.

The additional salt load on the catchment due to natural salt recharge is given as follows:

$$\mathrm{SNAT} \quad \mathrm{SRP} \times \mathrm{AREA} \tag{4.36}$$

Where:

SNAT = Salt load to natural recharge (tons)
SRP = catchment surface recharge rate for the pervious zone of the related salt wash-off sub-model (tons/km^2/ month)

The salt load leaving the various zones of the irrigated land is assumed to be proportionate to the respective TDS concentrations at the beginning of the month. Assume that the rejected water leaves at the TDS concentration of the applied irrigation water. Hence the salt load leaving the irrigated land by application rejection (surface runoff) can be calculated as follows:

$$\mathrm{SEND} = \mathrm{QSEND} \times \mathrm{CID} \tag{4.37}$$

SEND = salt load of rejected water (tons)

The salt load for the return flow from the upper storage zone, SUP (tons) is given by the following equation:

$$\mathrm{SUP} = \mathrm{SCU} \times \mathrm{QUP} \tag{4.38}$$

Where:

SCU = TDS concentration of the upper storage zone (mg/ℓ)

The sale load for the return flow from the lower storage zone, SLOW (tons) is given by the following equation:

$$\mathrm{SLOW} = \mathrm{SCL} \times \mathrm{QLOW} \tag{4.39}$$

Where:

SCL = TDS concentration of the lower storage zone (mg/ℓ)

In addition to the salt load entering and leaving the irrigated land, allow for a slow bleed-off of salt into deeper, inaccessible storage below the irrigated land. The salt loss below can be evaluated as follows

$$\mathrm{SLOSS} = \mathrm{PSL} \times \mathrm{SLL} \tag{4.40}$$

Where:

SLOSS = salt load lost during month to deep groundwater (tons)
PSL = proportion of salt load in lower soil moisture storage zone lost to deep storage
SLL = salt load in lower solid moisture storage zone at start of month (tons)

The salt load passed from the upper storage zone to the lower storage zone is evaluated using QLOW, the return flow through the lower zone and a deep percolation salt concentration factor. This factor accounts for the salt load in the upper zone washing into the lower zone. This salt load is given by the following equation:

$$\mathrm{SUTOL} = \mathrm{SCU} \times \mathrm{SCF} \times \mathrm{QLOW} \tag{4.41}$$

Where:

SUTOL = salt load passed from upper to lower storage zone (tons)
SCU = TDS concentration of upper storage zone (mg/ℓ)
SCF = deep percolation salt concentration factor

The salt balance continuity equation for the upper storage zone of the irrigation block sub-model is given by the following equation:

$$\mathrm{SLU_t} = \mathrm{SLU + SID + SLOAD + SNAT - SEND - SUP - SUTOL} \quad (4.42)$$

Where:

$\mathrm{SLU_t}$ = salt load in the upper zone at the end of month (tons)

The salt balance continuity equation for the lower storage zone of the irrigation block sub-model is given by the following equation:

$$\mathrm{SLL_t} = \mathrm{SLL + SUTOL - SLOW - SLOSS} \quad (4.43)$$

Where:

$\mathrm{SLL_t}$ = salt load in the lower zone at the end of the month (tons)

The total salt load leaving the irrigation block sub-model is given by the following equation:

$$\mathrm{SIR} = \mathrm{SEND + SUP + SLOW} \quad (4.44)$$

Where:

SIR = total salt load leaving the irrigation block (tons)
$= \mathrm{QIR \times CIR}$

After each year of irrigation application (the beginning of month 1), the gross irrigated area (scheduled irrigation area) can grow. To account for the additional salt load in the new irrigated area, a few assumptions are made.

First, any additional irrigated land is taken from the pervious zone area of the related salt wash-off sub-model for the catchment. Therefore the pervious zone area is reduced by the amount the irrigated area is increased.

The initial TDS concentrations of the new irrigated area is calculated such that the return flow seepage from the new portion of irrigated land is equal to the TDS concentration of the ground water storage in the salt wash-off sub-model of the associated catchment. This is calculated using the following equation.

$$\mathrm{CUP} = (\mathrm{CG \times (PRFU + PRFL)\ /\ (PRFU + PRFL \times SCF)} \quad (4.45)$$

Where:

CG = TDS concentration of the groundwater storage (mg/ℓ)

It is also assumed that the surface salt storage for that portion of the pervious zone in the salt wash-off sub-model of this catchment brought under irrigation is added to the upper storage zone of the irrigation block.

Hence the total salt load gain to the upper zone if given as follows:

$$\mathrm{SGU} = (\mathrm{HSU} \times \mathrm{CUP}\ /1000 + \mathrm{SP}) \times \mathrm{AD} \tag{4.46}$$

Where:

SGU = salt load gain in the upper storage zone (tons)
SP = unit salt storage in pervious zone of salt wash-off sub-model ($\mathrm{tons/km^2}$)
AD = increase in irrigated land area ($\mathrm{km^2}$)

The total salt gain to the lower zone is given as follows:

$$\mathrm{SGL} = \mathrm{HSL} \times \mathrm{CUP} \times \mathrm{SCF}\ /\ 1000 \times \mathrm{AD} \tag{4.47}$$

Where:

SGL = Salt load gain in the lower storage zone (tons)

For the salt wash-off sub-model the salt loss in the pervious zone, SLP (tons) is equal to:

$$\mathrm{SLP} = \mathrm{SP} \times \mathrm{AD} \tag{4.48}$$

and the salt loss in the groundwater zone, SLG (tons) is equal to :

$$\mathrm{SLG} = \mathrm{CG} \times \mathrm{HGW} \times \mathrm{AD}\ /\ 1000 \tag{4.49}$$

It is likely that the salt load gain in the irrigation block sub-model (SGU + SGL) will be greater than the salt load loss in the salt wash-off sub-model (SLP + SLG). This can be rationalised as the irrigation sub-model activating a deeper salt storage which was not available to the salt wash-off sub-model, due to the raising of the local water table form irrigation application.

If the gross irrigation supply requirements is met using flow from a dependent route, the salt load leaving the irrigation block sub-model using equations 4.1 to 4.49 can be expressed as:

$$\mathrm{SIR} = \mathrm{X3} + \mathrm{Y3_i} \times \mathrm{CD_i} \tag{4.50}$$

Where:

$\mathrm{X3} = \mathrm{SUP} + \mathrm{SLOW} + \mathrm{FACTOR} \times \mathrm{X}$ ……(4.51)
$\mathrm{Y3_i} = \mathrm{FACTOR} \times \mathrm{Y_i}$ ……(4.52)
$\mathrm{FACTOR} = \mathrm{QEND} \times (1.0 - \mathrm{TLPS}) \times \mathrm{QIG}\ /\ \mathrm{QID}$ ……(4.53)
$\mathrm{CIG} = \mathrm{X} + \mathrm{Y_i} \times \mathrm{CD_i}$, the salt concentration equation for the dependent route. ……(4.54)

Hence, the salt load leaving the irrigation block sub-model can be expressed in terms of a linear equation with one set of unknowns, the TDS concentration of the dependent route.

4.3 Irrigation Practice

The gross irrigation demand during the month must include an allowance for losses, which in turn is a function of the irrigation method employed, and for additional water for leaching salts out of the irrigated lands.

The following are typical irrigation efficiencies for different irrigation practices (Loxton Venn, 1985):

- Flood irrigation : 65 %
- Sprinkler irrigation : 75 %
- Centre pivot irrigation : 85 %
- Drip irrigation : 85 %

The mix of irrigation practices in various regions in the Vaal system gives the following overall efficiencies:

- Barrage to Bloemhof (riparian) : 73%
- Christiana : 74 %
- Vaalharts/Taung : 67 %
- Barkly West : 73 %
- Douglas – Bucklands : 69 %

For most irrigation schemes the leaching factor (LF) is known, or can be estimated from a knowledge of the mix of crops, soil types, drainage conditions, irrigation practice and the general quality of the applied water. For the purposes of this model LF is assumed constant for any irrigation scheme, although it is in effect a function of the quality of the applied irrigation water. This simplifying assumption is justified by the consideration that few farmers measure the salinity conditions in the root zone of their lands on a regular basis, and fewer still adjust the leaching fraction in accordance with changes in the measure salinity.

4.4 Irrigation return flow

An additional parameter was added to the standard WQT irrigation return flow equation, namely the canal transfer loss.

Some of the canal losses are lost from the system as result of evaporation and some can return to the natural or artificial draining systems through seepage as return flows.

$$\mathrm{RC} = \mathrm{Fc} \times \mathrm{QTLOS} \text{ was added to the total return flow from the system} \ldots\ldots\ldots\ldots(4.55)$$

Where:

RC = return flow seepage from canal losses (million m^3/month)
Fc = a factor between 0 and 1 and
QTLOS = canal transfer losses in water transport (million m^3/month)

The total return flow volume from the irrigation sub-model that is currently defined as:

$$\mathrm{RET} = (\mathrm{RE} \times \mathrm{AEFF} + \mathrm{RNE} \times \mathrm{ANEFF})/1000 \text{ has been changed to}$$

$$\mathrm{RET} = \mathrm{RC} + (\mathrm{RE} \times \mathrm{AEFF} + \mathrm{RNE} \times \mathrm{ANEFF})/1000 \quad \text{.. ....} (4.56)$$

Where:

RE = return flow seepage from effective irrigation area (mm)
AEFF = actual effective irrigated area (km^2)
RNE = return flow seepage from non-effective irrigation area (mm)
ANEFF = non-effective irrigated area (km^2)

5 WQT-SAPWAT METHOD IMPROVEMENTS

5.1 SAPWAT Representative Crop

It is not necessary for the WRSM/Pitman to capture all the detailed crop-irrigation system information required to calculate one representative crop, since this will be dealt with in irrigation pre-processor to be developed at a later stage.

The WQT module calculates the irrigation requirement using the following formula:

$$DIN = \sum_{i=1}^{\#crops} \left/ CPF_i \times \frac{(PE_m \times CF_{im} - ER_m)}{100} \right/ \ldots\ldots\ldots\ldots (5.1)$$

Where:

DIN = six monthly unit irrigation requirement [mm/month], where DIN ≥ 0
CPF_i = % of total irrigated area cultivated using crop i [%]
PE_m = potential evaporation for month m [mm/month]
CFi_m = crop i demand factor for month m [factor]
ER_m = monthly effective rainfall [mm/month]

Using the SAPWAT method of one representative crop means that:

$$PEm \times CFim \approx ET_{(crop)m} \ldots\ldots\ldots\ldots (5.2)$$

Where:

$ET_{(crop)m}$ = monthly Evapotranspiration values for the representative crop as obtained from area weighted crop/irrigation system........ SAPWAT values that occur in that area (mm/month)

Table 5.1: Parameter substitutions for WQT_SAPWAT method

WQT Parameter	WQT-SAPWAT Parameter / Value	Comment
#crops	1	One representative crop will be used in the WQT-SAPWAT method.
CPF_i	100%	The representative crop already takes into account all the crop/irrigation systems in the particular area.
PE_m	$ET_{(crop)m}$	The monthly potential evaporation must be replaced with the actual representative crops monthly evapotranspiration values.
CF_{im}	1	In all cases the crop factors are 1, since the PE_m value now represents the actual evapotranspiration of the representative crop.

5.2 Effective rainfall calculation

Using the WQT makes use of the following equation to determine effective rainfall:

$$\mathrm{ER_m} = \mathrm{ERF_m} \times \mathrm{Rain_m} \quad \text{.......} (5.3)$$

Where:

$\mathrm{ER_m}$ = monthly effective rainfall [mm/month]
$\mathrm{ERF_m}$ = 12 monthly effective rainfall factors, constant for each year[factor]
$\mathrm{Rain_m}$ = actual monthly rainfall [mm/month]

In addition, the WQT module makes use of two effective rainfall limits in the following manner:

If $\mathrm{Rain_m} > \mathrm{R_{lim(a)}}$

then:

$$\mathrm{ER_m} = \mathrm{ERF_m} \times \mathrm{Rain_m} \quad \text{.......} (5.4)$$

If $\mathrm{R_{lim(a)}} > \mathrm{Rain_m} > \mathrm{R_{lim(b)}}$

then:

$$ER_m = \left(1 - \frac{(1 - ERF_m) \times \left(R_{lim(a)} - Rain_m\right)}{R_{lim(b)} - R_{lim(a)}}\right) Rain_m \ldots\ldots\ldots (5.5)$$

If $\mathrm{Rain_m} < \mathrm{R_{lim(b)}}$

then:

$$\mathrm{ER_m} = \mathrm{Rain_m} \quad \text{.......} (5.6)$$

Where:

$\mathrm{ER_m}$ = monthly effective rainfall [mm/month]
$\mathrm{ERF_m}$ = 12 monthly effective rainfall factors, constant for each year[factor]
$\mathrm{Rain_m}$ = actual monthly rainfall [mm/month]
$\mathrm{R_{lim(a)}}$ = effective rainfall limit 1 [mm/month]
$\mathrm{R_{lim(b)}}$ = effective rainfall limit 1 [mm/month]

The SAPWAT formula for calculating effective rainfall is as follows:

$$ER_m = ET_{(cropm)m}\left(-0.001\frac{(Rain_m)^2}{ET_{(crop)m}} + 0.025\frac{(Rain_m)^2}{\left(ET_{(crop)m}\right)^2} + 0.0016 \times (Rain_m) + 0.6\frac{Rain_m}{ET_{(crop)m}}\right) \ldots\ldots (5.7)$$

Where:

ER_m = monthly effective rainfall [mm/month]

$ET_{(crop)m}$ = monthly representative crop evapotranspiration (requirement); where the maximum value of $ET_{(crop)m} = 75$ mm [mm/month]

$Rain_m$ = actual monthly rainfall [mm/month]

Table 5.2: Required effective rainfall changes for the WQT-SAPWAT

WQT Parameter	WQT-SAPWAT Parameter/Value	Comment
$R_{lim(a)}$ and $R_{lim(b)}$	0	Set both two rainfall limits to zero ensure that equation 3 is enforced.
Equation 3	Equation 6	The use of 12 effective rainfall factors should be replaced with a monthly calculation of the effective rainfall as in equation 6, with a maximum value of $ET_{(crop)m}$ = 75 mm

5.3 Drought reduction factors

This factor aims at simulating supplemental irrigation practices only, and should only be an option in the WRSM/Pitman. The factor simulates on a very elementary level farmers' supplemental irrigation planting practices, i.e. in dry months planting will be delayed until it rains, and in dry years the total irrigation will be reduced. These factors are not applicable in areas where there are high supply of water compared to the demand, such as Orange River irrigators in Upington.

The factor is proposed as being the following:

$$DF = Max\left(\frac{Rain_m}{Rain_{avg(m)}}, \frac{Rain_a}{Rain_{avg(a)}}\right)$$
$$where\ 0 \le DF \le 1 \ldots\ldots (5.8)$$

Where:

DF = monthly irrigation requirement drought reduction factor [factor]

$Rain_m$ = actual monthly rainfall for month m [mm/month]

$Rain_a$ = the total annual rainfall for the water year in which month m falls [mm/month]

$\text{Rain}_{\text{avg(m)}}$ = the monthly average rainfall for month m over the whole record period [mm/month]
$\text{Rain}_{\text{avg(a)}}$ = the annual average rainfall over the whole record period [mm/month]

The drought reduction factors are proposed to be implemented in the WQT-SAPWAT method as an option in the following manner:

$$DIN = DF \times \sum_{i=1}^{\#crops} \left/ CPF_i \times \frac{(PE_m \times CF_{im} - ER_m)}{100} \right/ \ldots\ldots\ldots\ldots (5.9)$$

Where:

DIN = monthly unit irrigation requirement [mm/month], where $\text{DIN} \geq 0$
DF = drought reduction factor calculated according to equation 7; where $0 \leq \text{DF} \leq 1$
#crops = 1 (one representative crop)
CPF_{i} = 100%
PE_{m} = $\text{ET}_{\text{(crop)m}}$ of the representative crop
CF_{im} = 1 (one representative crop, requirement equal to $\text{ET}_{\text{(crop)m}}$)
ER_{m} = calculated according to equation 6

6 IRRIGATION: WQT TYPE 4 METHODOLOGY (WR2012 STUDY) BY DR CE HEROLD

6.1 Introduction

The irrigation sub-module as used in the following models has been enhanced to account for several deficiencies in the previous versions of the sub-module:

- WQT Salt Washoff Model;
- The Water Resources Yield Model (WRYM) and
- The Water Resources Planning Model (WRPM).

The issues related with the previous versions of the sub-module were identified during the Berg River Water Availability Assessment Study. The return flow generated by the systems models for Western Cape climatic conditions was unrealistically high, due to most of the rain falling in the lowest evaporation period. The result was that the irrigation return flow calculation could not be used in this (and future) studies for this region which necessitated the use of time consuming alternative methods.

6.2 Improvements to the return flow calculation and effects on salt balances

The main concern identified was the way in which return flow is calculated in the water resources systems models. The return flow generated in the irrigation sub-module is based on the sub-surface soil moisture balance calculations. The soil moisture balance calculation did not yield realistic results in areas where most of the rainfall occurred in the period when the least evaporation occurred. A method of dealing with this problem was formulated and involved making changes to the two sub-surface soil moisture stores in the model. Additionally the functionality of accounting for canal losses that adds to return flow was implemented to also include the effect on salt balances. The algorithms used to simulate deep groundwater losses were also improved.

6.3 Irrigation demand calculations

Minor functionality improvements to the irrigation demand calculations in the water resources systems models were also made. These improvements are partly due to the changes being made to the return flow calculations and the salt balances, and partly to improve the WQT to have the same functionality that already exist in the WRSM/Pitman, WRYM and the WRPM. These changes include:

- Improved annual allocation limit calculations;
- Effects of drought requirement reduction on salt balances;
- Physical supply constraints functionality and
- FAO effective rainfall calculation.

6.4 Model Initialisation

6.4.1 Input Data Description

The input data description for the WQT model is provided in **Appendix A** of this document. The WRPM and WRYM input data formats are provided in the WRYM and WRPM Input Data and File Formats Documents for Version 4.4, dated 28 February 2013.

6.4.2 Starting salinity

At the start of the simulation the salt concentrations in the upper and lower soil zones are given as:

$$\mathrm{SCU_1} = \mathrm{RRSSUI} \tag{6.1}$$

$$\mathrm{SCL_1} = \mathrm{RRSSLI} \tag{6.2}$$

Where

$\mathrm{SCU_1}$ = Salt concentration in upper soil zone at start of the time step (t)
RRSSUI = Specified salt concentration upper soil zone (mg/ℓ)
$\mathrm{SCL_1}$ = Salt concentration in lower soil zone at start of the time step (t)
RRSSLI = Specified salt concentration lower soil zone (mg/ℓ)

The starting salt loads in the two soil zones are given by:

$$\mathrm{SLU_1} = \mathrm{SCU_1} \times \mathrm{AIRR_1} \times \mathrm{RRH0} \,/\, 1000 \tag{6.3}$$

$$\mathrm{SLL_1} = \mathrm{SCL_1} \times \mathrm{AIRR_1} \times \mathrm{RRHSL} \,/\, 1000 \tag{6.4}$$

Where

$\mathrm{SLU_1}$ = Salt load in upper soil zone at the start of the time step (t)
$\mathrm{RRH0}$ = Specified starting upper zone soil storage (mm)
$\mathrm{SLL_1}$ = Starting salt load in lower soil zone (t)
RRHSL = Specified total lower zone storage (mm)

The lower soil zone is assumed to remain saturated. Hence the storage remains constant at RRHSL (mm)

The following chemical application rates are also read in it at the start of the simulation:

$\mathrm{RRSLD_1}$ = Net salt load application from fertilizers, gypsum and agricultural lime less crop export during the 1st year of irrigation (REAL – t/ha/year)
$\mathrm{RRSLD_2}$ = Net salt load application from fertilizers, gypsum and agricultural lime less crop export during subsequent years (REAL – t/ha/year)

6.4.3 Time series input files

At initialisation the monthly time series files defined as input to the irrigation module are read in and stored in arrays.

Two types of time series file are associated with the Irrigation module, namely monthly rainfall and monthly irrigation abstractions. The general format of these input files is as follows:

Rainfall file:
Line 1: Repeat for all years
IYR = Hydrological year (INTEGER)
RAIN(12) = Monthly rainfall (% of MAP) (REAL)
Format : (4X,I4,1X,12(F6.0))

Irrigation abstraction file:
Line 1: Repeat for all years
IYR = Hydrological year (INTEGER)
QIS(12) = Actual monthly irrigation abstraction (10^6 m³) (REAL)
Format : (4X,I4,1X,12(F7.0,1X))

6.4.4 Fill annual arrays

At initialisation arrays of annual values are filled for the entire simulation period. These include annual values for irrigated areas, annual irrigation water allocations, transmission infrastructure capacities and irrigation efficiencies.

Algorithms for interpolating between the break point year values are dealt with elsewhere in the WQT program and are not described here as it they are common to other modules.

6.5 Start of Hydrological Year

6.5.1 Change annual values

At the start of each hydrological year the new irrigated area, annual irrigation water allocation, transmission infrastructure capacity and irrigation efficiency values are read from the prepared arrays for each irrigation module.

6.5.2 Salt load transfers to and from Salt Washoff module

The increase or decrease in the irrigated area at the start of each hydrological year results in the transfer of land and the associated salt loads between the catchment (SW module) and the irrigation module.

The increase in irrigated area at the start of each hydrological year is given by:

$$AD = AIRR_i - AIRR_{i-1} \quad \text{.....} (6.5)$$

Where

AD = Increase in irrigated area (km^2)
$AIRR_{i-1}$ = Irrigated area for previous hydrological year i-1 (km^2)
$AIRR_i$ = Irrigated area for current hydrological year, i (km^2)

Case 1: AD ≥ 0

If the irrigated area increases, then the pervious catchment area in the SW module is reduced by a like amount. The surface and sub-surface salt loads accumulated in that portion of the catchment that is captured for irrigation are then assumed to be transferred to the irrigation block.

The total salt load transferred to the irrigated land is then given as:

$$\mathrm{SGT} = (\mathrm{CG} \times \mathrm{SWHGW} / 1000 + \mathrm{SP}) \times \mathrm{AD} \qquad (6.6)$$

Where

SGT = Total salt load transferred to the irrigated land at start of hydrological year (t)

CG = Salt concentration of the groundwater storage in the SW module at the end of the pervious time step (mg/ℓ)

SWHGW = SW module groundwater storage depth (mm)

SP = Unit salt storage in the pervious zone of the SW module (t/km^2)

AD = Increase in irrigated land area (km^2)

The gain in salt load is assigned to the upper and lower soil zones in proportion to the storages:

$$\mathrm{SGU} = \mathrm{SGT} \times \mathrm{S2} \,/\, (\mathrm{S2} + \mathrm{RRHSL}) \qquad (6.7)$$

$$\mathrm{SGL} = \mathrm{SGT} - \mathrm{SGU} \qquad (6.8)$$

Where

SGU = Gain in salt load to upper soil zone (t)

RRHSL = Soil moisture storage in lower soil zone (t)

SGL = Gain in salt load to lower soil zone (t)

The new starting salt storages at the beginning of the year are then calculated as:

$$\mathrm{SLU}_{t-1} = \mathrm{SLU}_{t-1} + \mathrm{SGU} \qquad (6.9)$$

$$\mathrm{SLL}_{t-1} = \mathrm{SLL}_{t-1} + \mathrm{SGL} \qquad (6.10)$$

Where

SLU_{t-1} = Salt storage in upper soil zone at start of time step (t)

SLL_{t-1} = Salt storage in lower soil zone at start of time step (t)

For the SW module, the loss in the pervious zone surface salt storage, SLP (t), is equal to:

$$\mathrm{SLP} = -\,\mathrm{SP} \times \mathrm{AD} \qquad (6.11)$$

The salt loss from the groundwater storage of the SW module, SLG (t), is given by:

$$\mathrm{SLG} = -\,\mathrm{CG} \times \mathrm{AD} \times \mathrm{SWHGW} \,/\, 1000 \quad (6.12)$$

Case 2: AD < 0
If the irrigated area decreases, then the corresponding portion of the salt load must be transferred to the SW module.

The reductions in the salt load stored in the upper and lower soil zones are calculated as:

$$\mathrm{SGU} = \mathrm{SLU}_{t-1} \times \mathrm{AD} \,/\, \mathrm{AIRR}_{i-1} \quad (6.13)$$

$$\mathrm{SGL} = \mathrm{SLL}_{t-1} \times \mathrm{AD} \,/\, \mathrm{AIRR}_{i-1} \quad (6.14)$$

There is insufficient information to assign a proportion of the transferred salt load to the pervious catchment surface store in the SW module. Instead the entire load is transferred to the subsurface salt storage. This approximation implies that the previous irrigation will have depleted the amount of salt stored at the surface and available for washoff. The effect of the approximation is further diminished provided the irrigated area is small compared to the total catchment area and the fact that irrigated areas seldom decline. The increases in the salt storages in the SW module are therefore:

$$\mathrm{SLP} = 0 \quad (6.15)$$
$$\mathrm{SLG} = \mathrm{SGU} + \mathrm{SGL} \quad (6.16)$$

6.6 Monthly Loop

6.6.1 Irrigation water demand

Net unit demand

Two options are allowed in the new model to calculate the effective rainfall:

- The modified WQT method and
- The SAPWAT method.

Modified WQT method

Calculation of the monthly unit irrigation demand is based on the algorithms used in the original WQT model (Allen and Herold, 1988).

The monthly unit irrigation demand before allowances for losses, DIN (mm) is calculated as:

$$DIN = \sum_{i=1}^{NCPS} \Big/ \frac{CPF_i}{100} \times (PE_m \times CF_{im} - ER_m) \Big/ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.17a)$$

Where

DIN = Monthly irrigation demand excluding losses (mm)
NCPS = Number of crops
i = i^{th} crop
m = Hydrological month (1 = October, 12 = September)
CPF_i = Percentage of total irrigated area cultivated using crop "I"
PE_m = Mean monthly potential A-pan evaporation for month m (mm)
CF_{im} = Mean monthly crop demand factor for crop i for month m
ER = Effective monthly rainfall (mm)

If DIN is less than zero, then DIN is set to zero.

The effective rainfall, ER, is used in place of the actual month's rainfall to allow for the fact that there is a time lag (often several hours) between the call for irrigation water and the arrival of the scheduled water at field edge, due to transmission through the canal system. Administrative factors add to this delay. If it rains in the meantime, then part of the irrigation water will be wasted. High rainfall events can also exceed the infiltration rate of the soil, resulting in surface runoff thereby making part of the rainfall inaccessible to the crop. It must also be observed that the rainfall distribution during a month (the computational time step) is not uniform. Thus for part of the month (usually a short part) the rainfall may exceed the crop demand, while for the rest of the month there may be no rainfall at all, necessitating more irrigation application than might have been surmised had the month's rainfall been uniform. This temporal variation means that the effective rainfall factor will almost invariably be smaller than the rainfall factor based on daily rainfall data. This distinction is extremely important when choosing effective rainfall factors.

At the other end of the scale, for low rainfall, it is generally assumed that nearly all of the rainfall is effective since none of the rainfall will be spilled or exceed the infiltration rate of the soil. However, it could be argued that under such conditions the rainfall may be too low for the farmer or dam operators to take into account when scheduling releases. Or some of the rainfall may be lost to canopy interception without reaching the ground. For this reason the modified WQT version allows the user to specify an upper limit to the effective rainfall factor.

The effective rainfall factor, ERF, is defined as a function of the month's rainfall. This relationship is illustrated in Figure 6.1. This factor is multiplied by the month's rainfall to obtain the effective rainfall (ER).

The monthly effective rainfall is assumed to be controlled by the following three conditions:

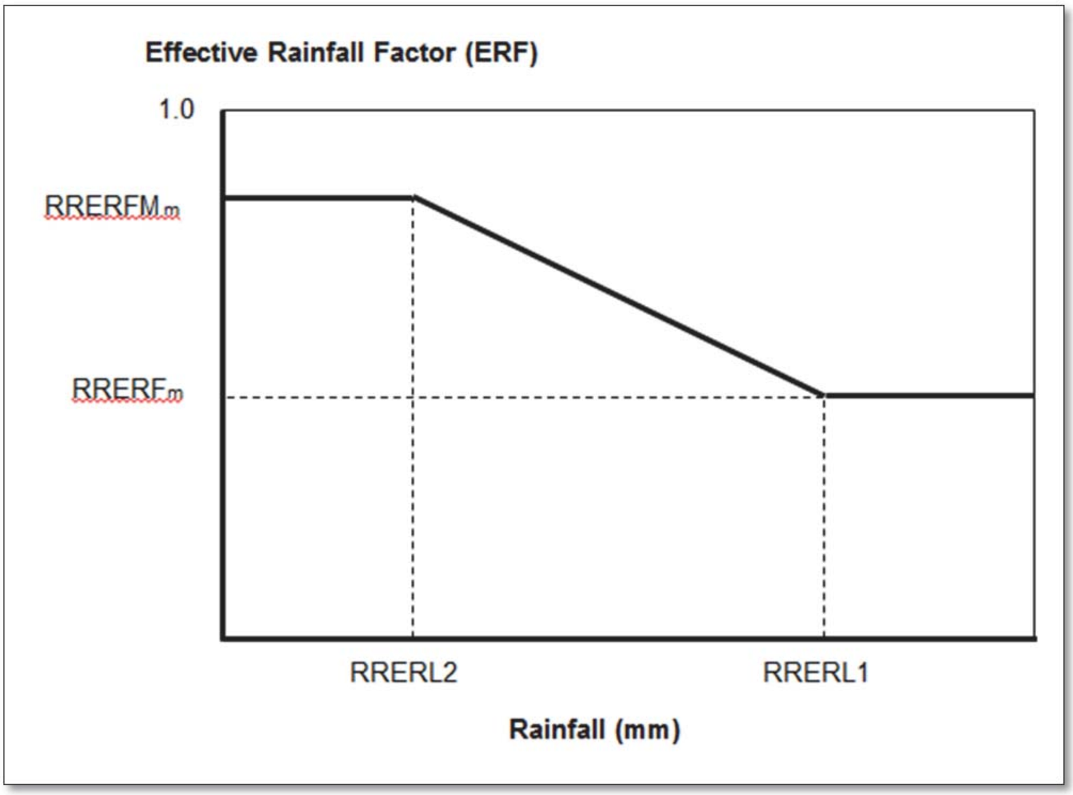


Figure 6.1: Definition of effective rainfall factor

(i) Condition 1: $\mathrm{RAIN} < \mathrm{RRERL2}$:

$$\mathrm{ERF} = \mathrm{RRERFM_m} \ldots\ldots (6.18a)$$

Where

ERF = Effective rainfall factor
RAIN = Month's rainfall (mm)
RRERL2 = Lower rainfall limit (mm)
RRERFM = Maximum effective rainfall factor for month m

The only difference between the modified and original WQT methods for estimating ER lies in the addition of the factor RRERFM$_m$, which allows more flexibility. (The original version assumed an effective rainfall factor of 1.0 when the rainfall is below RRERL2, i.e. RRERFM$_m$ was fixed at 1.0.)

(ii) Condition 2: $\mathrm{RRERL2} < \mathrm{RAIN} < \mathrm{RRELRL1}$

$$ERF = RRERF_m + \frac{(RRERFM_m - RRERF_m) \times (RRERL1 - RAIN)}{(RRERL1 - RRERL2)} \ldots\ldots (6.18b)$$

Where

$\mathrm{RRERF}_{\mathrm{m}}$ = Minimum effective rainfall factor for month m
RRERL1 = Upper rainfall limit (mm)

(iii) Condition 3: RAIN > RRERL1
ERF = $\mathrm{RRERF}_{\mathrm{m}}$ .... (6.18c)

The following limits apply:

0 < RRERF~~m~~ ≤ RRERFM~~m~~ ≤ 1.0

And

$0 \leq \mathrm{RRERL2} \leq \mathrm{RRERL1}$

The effective rainfall is then given by:

ER = ERF × RAIN .... (6.19a)

SAPWAT method
The SAPWAT method follows similar calculation techniques for the net unit irrigation demand, but has been pre-applied to each quaternary catchment taking account of the areas of land under different crops. The results have been aggregated to form an effective single crop for the quaternary. Hence equation (6.17a) simplifies to:

DIN = ET~~m~~ – ER .... (6.17b)

Where

ET_{m} = Mean monthly evapotranspiration loss for the representative crop, which is equivalent to the term $\mathrm{PE}_{\mathrm{m}} \times \mathrm{CF}_{\mathrm{m}}$ in Equation (6.17a) (mm).

The SAPWAT method calculates the effective rainfall for the month as:

$$ER = ET_m \times \left(-0.001\frac{(Rain)^2}{ET_m} + 0.025\frac{(Rain)^2}{(ET_m)^2} + 0.0016 \times (Rain) + 0.6\frac{Rain}{ET_m}\right) \ldots\ldots (6.19b)$$

6.6.2 Field edge irrigation demand

The monthly field edge irrigation demand needs to account for the area irrigated and the irrigation efficiency.

$$QID = AIRR_i \times \frac{DIN}{1000} \times \frac{1}{RRIE_i} \dots\dots (6.20)$$

Where

QID = Field edge irrigation demand (10^6 m^3)
AIRR_i = Irrigated area for hydrological year i (km^2)
RRIE_i = Irrigation efficiency factor (-)

The user provides irrigated areas for each specified break point year. Either linear or exponential interpolation can be used to calculate the areas, $AIRR_i$, for each intermediate year, i. An upper limit on the allowable irrigated area is: $0 \le AIRRi \le (SWA – SWUA)$, where SWA (km^2) is the total catchment area and SWUA (km^2) is the urbanised area.

The irrigation efficiency factor accounts for different irrigation practices not applying the water uniformly over the irrigated land, resulting in wastage. Flood irrigation has the lowest efficiency, drip irrigation the highest. Typical irrigation efficiency factors are as follows (Loxton Venn, 1985):

Flood irrigation	:	65%
Sprinkler irrigation	:	75%
Centre pivot irrigation	:	85%
Drip irrigation	:	85%

One difficulty associated with the irrigation efficiency is the fate of the “inefficient” proportion of the water applied. DIN purports to account for the water balance of the soil since it is assumed to maintain the soil moisture at an optimum level. It follows that any additional water applied to the land must either give rise to additional return flow or result in additional evapotranspiration loss. Loxton Venn (1985) estimated the irrigation efficiency at the Vaalharts irrigation scheme as 67%. This implies an additional 33% application to the irrigated lands. However, hydrological analyses of the Harts River carried out by Pitman (1987) for a similar period showed an annual return flow of 30 m³ × 10^6, which was only 10% of the water supply to Vaalharts. This implies that supply inefficiency must have resulted in additional evapotranspiration losses of 23% (although some of this may have been lost to deep seated groundwater in this semi-arid region).

6.6.3 Drought reduction factor

An option is provided to use a drought reduction factor, if applicable. This factor is as provided in the WRSM/Pitman model and is aimed at simulating supplemental irrigation practices only. The factor simulates on a very elementary level farmers’ supplemental irrigation planting practices. I.e. in dry months planting will be delayed until it rains, and in dry years the total irrigation will be reduced. This factor is not applicable in areas where the water availability is large compared to the demand, such as Orange River irrigators in Upington.

This factor is calculated as:

$$DF = Max\left(\frac{Rain}{Rain_{(m)}}, \frac{Rain_a}{MAP}\right) \; where \; 0 \leq DF \leq 1 \ldots\ldots\ldots\ldots\ldots\ldots (6.21a)$$

Where

DF = Drought reduction factor
RAIN = Actual rainfall for month (mm)
RAIN_m = Mean monthly rainfall for month m (mm)
RAIN_a = Annual rainfall for the current water year (mm)
MAP = Mean annual precipitation (mm)

A weakness of Equation (6.21a) is that it supposes prior knowledge of the year's rainfall, RAIN_a. While this can be calculated by the model, in reality no farmer will know in advance what total rainfall will occur during the year. It is clear that the use of the drought reduction factor is at best an approximation.

For all other cases DF is deactivated as follows:

$$\text{DF} = 1.0 \ldots\ldots\ldots\ldots (6.21b)$$

The adjusted net unit irrigation demand, DIN1 (mm) is then calculated as:

$$\text{QID1} = \text{QID} \times \text{DF} \ldots\ldots\ldots\ldots (6.22)$$

6.6.4 Irrigation demand at supply source

Allowance has to be made for transmission losses through the conveyance system to arrive at the gross water demand at the point of abstraction from the water source.

$$QIG = QID1 \times \frac{1}{1 - RRTLPQ} \ldots\ldots\ldots\ldots (6.23)$$

Where

QID1 = Gross irrigation demand at raw water supply source (10^6 m^3)
RRTLPQ = Proportion of supply water lost in conveyance system (-)

6.6.5 Water allocation constraints

Equation (6.23) represents the irrigation demand at the supply source. However, this full demand may not be met for the following reasons:

- Conveyance system and/or on farm system constraints
- Permissible allocation limit exceeded
- Insufficient water at source.

System capacity constraints

The month's water supply cannot exceed the capacity of the canal or pipeline supplying the irrigated land, or of the on-farm irrigation system. In effect there is no need to differentiate between the two types of constraint seeing as the WQT model simulates an entire irrigation module, in which the ruling constraint is all that matters. Hence the following checks have been included:

$$\text{If} \quad QIG > RRCAP_i$$
$$QIG = RRCAP_i \qquad \text{(6.24)}$$

where $RRCAP_i$ is the limiting capacity of the system for year i (10^6 m³ /month)

Provision is made to specify the capacities at breakpoint years and the method of interpolation to be used between specified breakpoints (linear or power).

Permissible annual allocation limit exceeded

The original WQT irrigation module allows for a specified maximum annual water allocation, $RRMA_i$ (10^6 m³). This is sound in principle, but was applied too simplistically, since it allowed full satisfaction of the monthly water demand until such time as the annual allocation was exceeded, after which irrigation ceased for the remainder of the hydrological year.

The following procedure is intended to yield a more realistic distribution of the annual water allocation to the months of the year.

Since the actual monthly rainfall for the remaining months of the year is never known in advance, it is necessary to devise a distribution based on mean monthly rainfall data and adjust the allocation available as the year progresses. The monthly distribution factors are pre-calculated as:

$$DFAC_m = \frac{DINM_{im}}{\sum_{M=1}^{12} DINM_{im}} \qquad \text{(6.25)}$$

Where

$DFAC_m$ = Mean distribution factor for hydrological month m (-)

$DINM_m$ = Mean net unit irrigation demand for month m

For the modified WQT method, $DINM_m$ is pre-calculated from Equations (6.17a), (6.18a), (6.18b), (6.18c) and (6.19a), except that the variable RAIN (the actual month's rainfall) is substituted with $RAINM_m$ (the mean rainfall for month m). $RAINM_m$ is calculated as:

$$RAINM_m = \frac{1}{NY} \times \sum_{i=1}^{NY} (RAIN_{i,m}) \ldots\ldots (6.26)$$

Where

NY = Number of hydrological years in rainfall dataset
i = Hydrological year
m = Hydrological month (1 = October, 12 = September)
$RAIN_{i,m}$ = Rainfall during month m of year i (mm)

For the SAPWAT method, $DINM_m$ is pre-calculated from Equations (6.17b) and (6.19b), with the variable RAIN replaced by $RAINM_m$.

The original WQT irrigation module used growth factors that were multiplied by a single defined allocation (parameter RRMA) for GROWTH = 1.0. In the modified version the growth factor is dropped and instead the user directly species the actual allocation amounts for each breakpoint year, $RRMA_i$ (10^6 m³). Linear or power regressions are chosen for interpolation between the breakpoints.

The nominal water allocation for each month is then calculated as:

$$DALOC = DFAC_m \times RRMA_i \ldots\ldots (6.27)$$

Where

DALOC = Nominal water allocation for the month m (10^6 m^3).
$RRMA_i$ = Annual water allocation for year i (10^6 m^3)

For the first month of the hydrological year the month's allocation is fixed by Equation (6.27), but thereafter the unused portion of the allocation for previous months that have already passed is accumulated:

At the start of every hydrological year the accumulated surplus, ACCALOC, is set to zero:

$$ACCALOC = 0 \ldots\ldots (6.28a)$$

Where

ACCALOC = Accumulated surplus available for allocation to future months (10^6 m^3)

This implies that surplus allocations are not carried forward from one hydrological year to the next.

For each month simulated we then have:

If $\mathrm{QIG} \leq \mathrm{DALOC}$

$$\mathrm{ACCALOC} = \mathrm{ACCALOC} + \mathrm{DALOC} - \mathrm{QIG} \tag{6.28b}$$

Else if $\mathrm{QIG} > \mathrm{DALOC}$

If $\mathrm{QIG} \leq \mathrm{DALOC} + \mathrm{ACCALOC}$

$$\mathrm{ACCALOC} = \mathrm{DALOC} + \mathrm{ACCALOC} - \mathrm{QIG} \tag{6.28c}$$

Else if $\mathrm{QIG} > \mathrm{DALOC} + \mathrm{ACCALOC}$

$$\mathrm{QIG} = \mathrm{DALOC} + \mathrm{ACCALOC} \tag{6.29}$$

$$\mathrm{ACCALOC} = 0 \tag{6.28a}$$

Application of a water allocation limit is most applicable to controlled water schemes. It is not appropriate for diffuse opportunistic irrigation where the main limitations are the physical capacity of the abstraction and conveyance system and the intermittent availability of water in the river. In such instances it may be appropriate to set the water allocation to a large value, which will effectively ensure that water allocation does not limit abstraction

Insufficient water at source

The amount of water that can be abstracted for irrigation is limited by the available flow in the river or the storage in supporting dams. This is especially true of diffuse opportunistic irrigation that is dependent on the temporal variation in catchment runoff.

The original WQT model network solver already accounts for supply side limitation for riparian irrigation. Modification to allow for this is therefore not required.

Irrigation abstractions pre-defined

If a file of actual monthly gross irrigation abstractions is specified, then these will define the QIG values and the constraints discussed in Sections 6.6.5 and 4.5.2 will not apply. This also renders it unnecessary and contradictory to calculate the field edge demand (Section 4.1.2), the drought reduction factor (Section 4.1.3) and the demand at the supply source (Section 4.1.4), all of which are bypassed.

6.6.6 Actual application

After reduction of QIG1 due to the various constraints discussed in Section 4.1.5, the amount of water supplied, QIG, will have been reduced by transmission losses. This means that the amount of water actually applied to the irrigated land will also be reduced.

From Equation (6.23), the irrigation discharge reaching the point of supply (assumed to be at the end of the canal), QIS1 (10^6 m³), is given by:

$$\mathrm{QIS1} = \mathrm{QIG} \times (1 - \mathrm{RRTLPQ}) \quad (6.30)$$

Part of the transmission loss is in the form of evaporation loss from the canal water surface. The remainder is lost as seepage to groundwater from canals. For water quality modelling it is necessary to differentiate between the two, since the evaporation loses only water and not the salt, which remains in the supply, whereas seepage loss removes both water and salt.

The evaporative portion of the canal loss and the seepage loss are given by:

$$\mathrm{QTLE} = \mathrm{QIG} \times \mathrm{RRTLPQ} \times \mathrm{RRTLPE} \quad (6.31)$$

$$\mathrm{QTLS} = \mathrm{QIG} \times \mathrm{RRTLPQ} \times (1 - \mathrm{RRTLPE}) \quad (6.32)$$

Where

QTLE = Evaporation loss from canal surface (10^6 m^3)
RRTLPE = Proportion of transmission loss to evaporation ($0 \leq \mathrm{RRTLPE} \leq 1$)
QTLS = Seepage loss from canals (10^6 m^3)

The WRSM/Pitman model allows for a portion of the transmission seepage loss to enter the return flow. Since the evaporation loss is unavailable for this purpose, the portion of the canal loss entering the return flow is given by:

$$\mathrm{QTLR} = \mathrm{QTLS} \times \mathrm{RRPTLR} \quad (6.33)$$

Where

QTLR = Transmission loss routed to return flow (10^6 m^3)
RRPTLR = Portion of transmission seepage loss to return flow ($0 \leq \mathrm{RRTLPE} \leq 1$)

The seepage from the supply canals lost to deep seated groundwater, QTLD (10^6 m³), is calculated as:

$$\mathrm{QTLD} = \mathrm{QTLS} - \mathrm{QTLR} \quad (6.34)$$

Spillage from furrow and canal ends

Part of the irrigation supply is assumed to spill from the ends of canals and furrows in the same month that it is applied. It is reasonable to assume that the end of canal spillage forms part of the irrigation efficiency loss. The end of canal spillage loss, QEND (10^6 m³), is calculated as:

$$\mathrm{QEND} = \mathrm{QIS} \times \mathrm{RRPEND} \quad \text{......}(6.35)$$

Where:

RRPEND = Proportion of irrigation supply spilled from canal ends.

From equations (6.30) and (6.35) the actual application to the irrigated land, QIS (10^6 m³), comes to:

$$\mathrm{QIS} = \mathrm{QIG} \times (1 - \mathrm{RRTLPQ}) \,/\, (1 + \mathrm{RRPEND}) \quad \text{......}(6.30a)$$

6.6.7 Irrigation return flow

Earlier catchment models

The original WRSM90 water quantity model calculated the irrigation return flow as a simple proportion of the irrigation application. The reasoning behind this was that for a catchment where the irrigated area is relatively small compared with the catchment size, the main change to catchment runoff due to irrigation would be a return flow proportional to the irrigation application. The catchment rainfall-runoff model already accounts for the surface and groundwater flow associated with rainfall. This is an approximation since cultivation would increase the interception loss and also affect the soil moisture-evapotranspiration characteristics. A wetter soil at the onset of rainfall events would also affect surface runoff. This is a reasonable assumption for water quantity provided the irrigated area is relatively small compared with catchment area. It also holds the advantage that the irrigation return flow can easily be defined as a percentage of application.

However, the disadvantage is that as the rainfall increases, the return flow is assumed to decrease in step with the reducing irrigation application, and cease entirely once the effective rainfall exceeds the irrigation demand (see Figure 6.2).

This model is particularly disadvantageous for salinity modelling since as the rainfall increases there is less and less modelled water available to transport the large amounts of salt contained in the irrigation return flows. This results in illogical changes in the salinity of base flows downstream of irrigated areas.

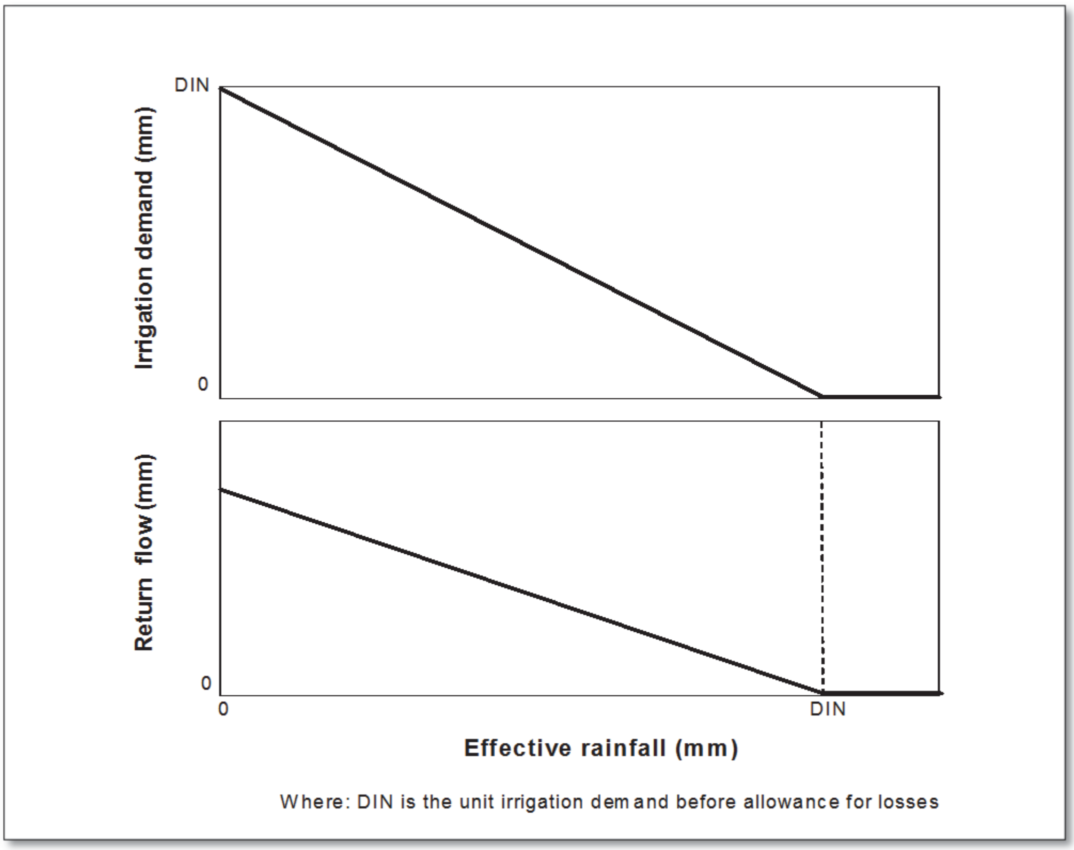


Figure 6.2: Old WRSM90 irrigation return flow model

Hypothesised process

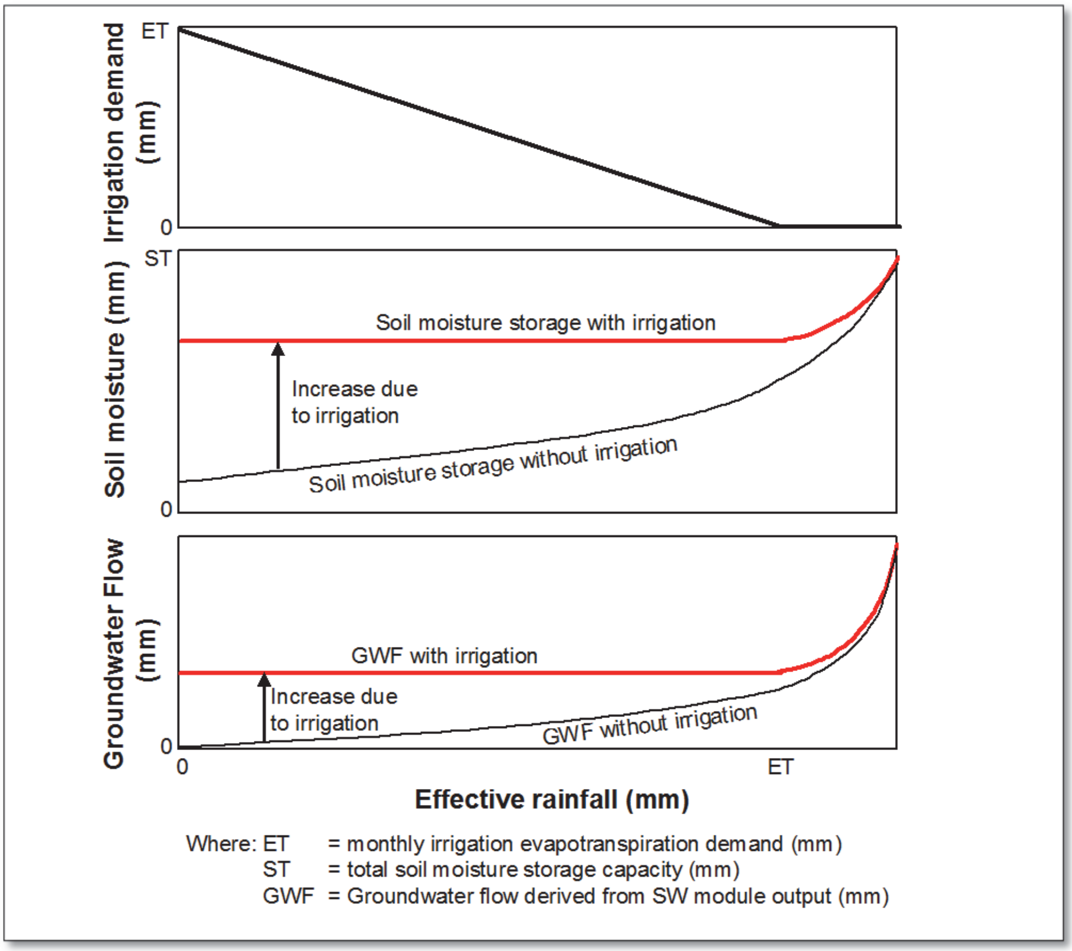
Figure 6.3 shows the hypothesised change in both soil moisture storage and groundwater flow as the rainfall increases.

As before, the top portion of Figure 6.3 shows a linear decrease in irrigation requirement as the effective rainfall, ER, increases and satisfies an increasing proportion of the irrigation demand, ET. Once the effective rainfall exceeds the crop demand, the irrigation demand ceases.

The black line in the middle portion of the plot shows an increase in the soil moisture storage with increasing rainfall. This is not a linear relationship, since as the soil moisture increases more water is lost to evapotranspiration and runoff. Irrigation has the effect of keeping the soil moisture content, as denoted by the red line, sensibly constant on a monthly basis. (During the month several cycles of irrigation application would occur. Typically each application would raise the soil moisture to field capacity, after which the soil moisture would decline to say half way to the wilting point, after which the next application would again raise the storage to the field capacity, and so on. But the monthly average would remain at some optimum value.) Only once the effective rainfall exceeds the crop demand, ET, would the average monthly soil moisture storage rise above this optimum.

It is logical to assume that the groundwater flow, shown in the bottom portion of the plot, would be driven by the soil moisture storage, resulting in a sensibly constant irrigation return flow when the effective rainfall is in the range 0 to ET mm. Thereafter it would rise after the effective rainfall exceeds the crop demand in response to the increasing soil moisture storage. This would also give rise to increasing surface runoff.

In the original WQT irrigation model an attempt was made to coarsely track the soil moisture storage and relate the irrigation return flow to this. This stopped short of trying the replicate all of the hydrological processes accounted for in the Runoff Unit (Pitman model) WRSM/Pitman rainfall-runoff model, but it did lead to overlap with some of the functions of the catchment runoff sub-model. These inconsistencies are small for arid and semi-arid areas, but become more pronounced for more humid areas, especially so for high rainfall winter rainfall areas where during the rain season the monthly rainfall frequently exceeds the potential evaporation.



Where: ET = monthly irrigation evapotranspiration demand (mm)
ST = total soil moisture storage capacity (mm)
GWF = Groundwater flow derived from SW module output (mm)

Figure 6.3: Hypothesised change in soil moisture and groundwater flow

Modified WQT irrigation return flow

The modified WQT irrigation module is aimed at redressing these problems and at the same time to reduce the complexity of some of the algorithms.

The modified version uses the following guiding principles:

- The irrigation module and the catchment rainfall-runoff module (Salt Washoff (SW) module in the WQT model) should not overlap one another's functions in the generation of runoff;
- The irrigation module must account for the increase in groundwater flow attributable to the irrigation application and
- The irrigation return flow needs to be spread more uniformly over time when the effective rainfall is less than the crop demand.

Two basic approaches could perform these functions:

- Excise the irrigated area entirely from the SW module and develop a comprehensive irrigation module for this area that encompasses all rainfall-runoff processes and irrigation processes and
- Use the SW model to account for rainfall-runoff processes and add the effect of irrigation application.

The first approach would offer a comprehensive solution and could be based on the Pitman model, with irrigation application simply acting as an enhanced rainfall to the irrigated sub-catchment. However, this approach would require solving the problem of relating potential evaporation values used in the Pitman model to the crop demand factors used for irrigation. Moreover, it must be recognised that the WQT model not only has to be able to be calibrated; its algorithms also have to be used in the WRPM, which uses stochastically generated runoff as its primary driving force. Hence an observed rainfall dataset will not always be available to drive a rainfall-runoff modelling process.

For these reasons the second approach was adopted.

Figure 6.4 shows the assumed water fluxes and storages used in the irrigation module. The variables used are defined in the following sections.

Irrigation return flow associated with irrigation application

The return flow associated with the irrigation application is made up of the following components:

- Return flow from upper soil zone;
- Return flow from lower soil zone;
- Loss to deep-seated groundwater and
- Spillage from ends of furrows and canals.

The applied irrigation water is assumed to enter into a store that gives rise to irrigation return flow and seepage to deep groundwater. This store is coarsely analogous to, but not identical with, the soil moisture storage. The processes governing the water balance of the normal (un-irrigated) portion of the catchment are already implicitly included in the catchment runoff used as input to the SW module and used as input to the irrigation module. The irrigation module treats the additional irrigation application separately. This approximation is necessary since any attempt to link the return flow to the entire soil moisture storage would inevitably result in duplication of the function of the SW module, thereby resulting in over-estimation of the runoff from the irrigated area. It must also be recognised that the inefficiency of the irrigation process (see Section 6.6.2) means that when the full irrigation demand is satisfied the total amount of water entering the irrigated land can substantially exceeds the crop demand and the observed return flow. Rigorous modelling of the irrigated land would of necessity mean having to account for this additional water loss. This is beyond the scope of this simplified irrigation model. (Nor does it appear to have been addressed adequately in most other irrigation models.)

Aside from addressing the above factors, the modified WQT model needs to account for the fact that the full irrigation requirement is not always met, for the reasons given in Section 4.1.5. The land could also lie fallow for part of the year. During such conditions a drop in the irrigation-induced return flow can be expected, and this must be completely exhausted when irrigation ceases. To account for this the concept has been introduced of a pseudo tank to store the irrigation supply less the net crop demand and irrigation return. This is roughly analogous to the soil moisture storage, ignoring the effect of normal catchment processes, which are accounted for by the SW module.

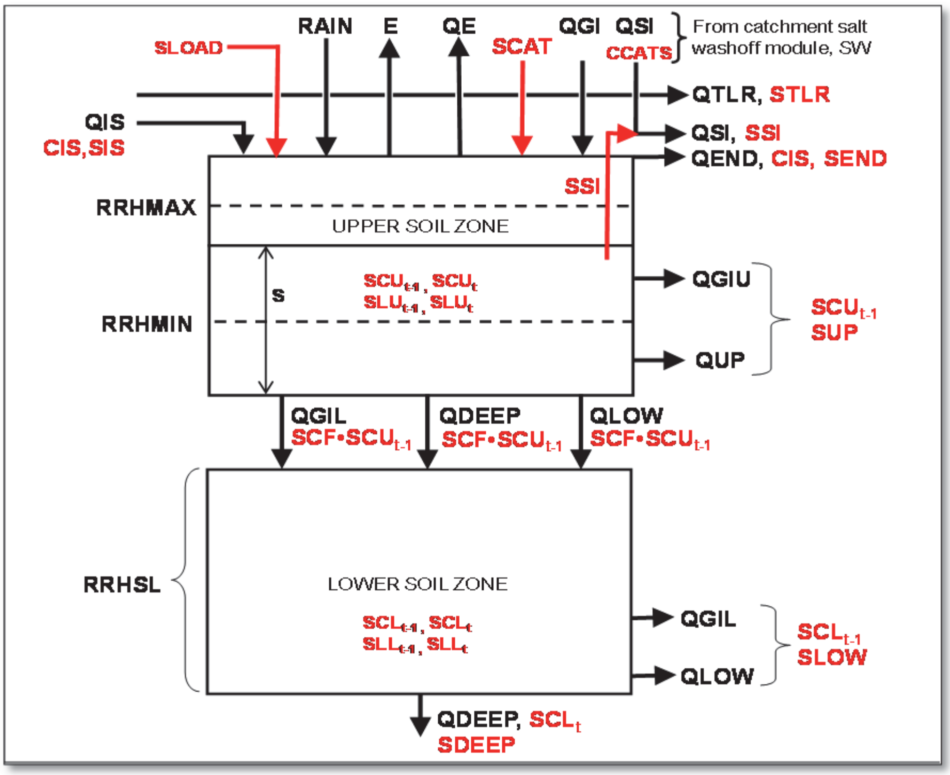


Figure 6.4: Representation of sub-surface storages and flows

Two sub-surface storage tanks are used. The upper tank deals with upper portion of the soil profile down to the bottom of the root zone. A second tank below this is used to account for the portion of the underlying groundwater that discharges back to the river.
The features of the two sub-surface storage tanks are shown in Figure 6.4 .

The water balance for the upper soil zone is given by:

$$S2 = S1 + RAIN - E + (QIS - QUP - QLOW - QDEEP + QGI - QGIU - QGIL) \times (1000/AIRR_1) \quad (6.36)$$

Where

S2 = Storage depth at end of month (mm)
S1 = Storage depth at start of month (mm)
QUP = Irrigation return flow to surface from upper storage zone (10^6 m^3)
QLOW = Irrigation return flow to surface from lower storage zone (10^6 m^3)
DEEP = Percolation loss to deep-seated groundwater (10^6 m^3)
QGI = Portion of catchment groundwater flow and interflow passing through the irrigated land (10^6 m^3)
QGIU = Component of pervious catchment runoff returned from upper soil zone (10^6 m^3)
QGIL = Pervious catchment runoff returned from lower soil zone (10^6 m^3)
= QGI – QGIU

By the above definitions equation (6.36) can be simplified since the term QGI – QGIU – QGIL = 0. However, these terms have been retained since they assume significance in the salinity calculations (described in Section 4.3).

The total return flow associated with the irrigation application, QIOUT (=QUP+QLOW) (10^6 m³), is assumed to cease when the soil storage drops to RRHMIN:

$$\mathrm{QIOUT} = (0.5 \times (\mathrm{S1} + \mathrm{S2}) - \mathrm{RRHMIN}) \times \mathrm{RRLF} \times (\mathrm{AIRR}_1 / 1000) \quad (6.37)$$

Where

RRHMIN = Minimum storage (mm)
RRLF = Return flow factor (-)

It must be recognised that through using crop factors the irrigation module deals with evapotranspiration differently to the ration the catchment modelling. As a result the modelled irrigation return flows are a simplifying approximation.

Equations (6.36) and (6.37) applicable for estimating the additional sub-surface return flow associated with the irrigation for months when irrigation application actually takes place. This actually overlaps the groundwater flow component of the catchment runoff time series used as input to the Salt Washoff (SW) module. Calibration of the RRLF parameter provides a means of adjusting the net irrigation return flow to match the observed runoff at downstream river and reservoir gauging stations.

However, during months when crop factors are low and/or the rainfall is high enough to satisfy the irrigation demand (i.e. when QIS is zero) it is necessary to avoid duplication of the excess runoff generated by the catchment runoff module. Since the irrigation module does not deal with the more complex rainfall-runoff processes and this is accommodated by the catchment runoff time series used as input to the Salt Washoff (SW) module. In fact, after a period of zero irrigation application the runoff from the irrigated portion of the land should behave much like any other part of the wider catchment. This effect can be accommodated by setting the irrigation return flow to zero when QIS drops to zero. (The normal catchment runoff time series would then fully account for the runoff.) However, doing so would imply an abrupt discontinuity in the soil moisture storage in the irrigation area. In reality, before the onset of the excess rain event the soil moisture would start off higher than that in the natural catchment, thereby causing an increase in runoff at the start of the wetter period, with the difference declining under the influence of evapotranspiration (or disappearing rapidly after the soil moisture storage capacity is exceeded). A simple means of mimicking this effect on the net return flow is to artificially set the rainfall input to zero. This causes the net influence of the irrigation on soil moisture storage (and hence return flow) to decline smoothly in a more realistic fashion.

Hence when QIS = 0, Equation (6.36) is reduced to:

$$S2 = S1 - E + (QIS - QUP - QLOW - QDEEP + QGI - QGIU - QGIL) \times (1000/AIRR_1) \qquad (6.36a)$$

Figure 6.5 illustrates the variation of the simulated return flow with irrigation application and catchment runoff.

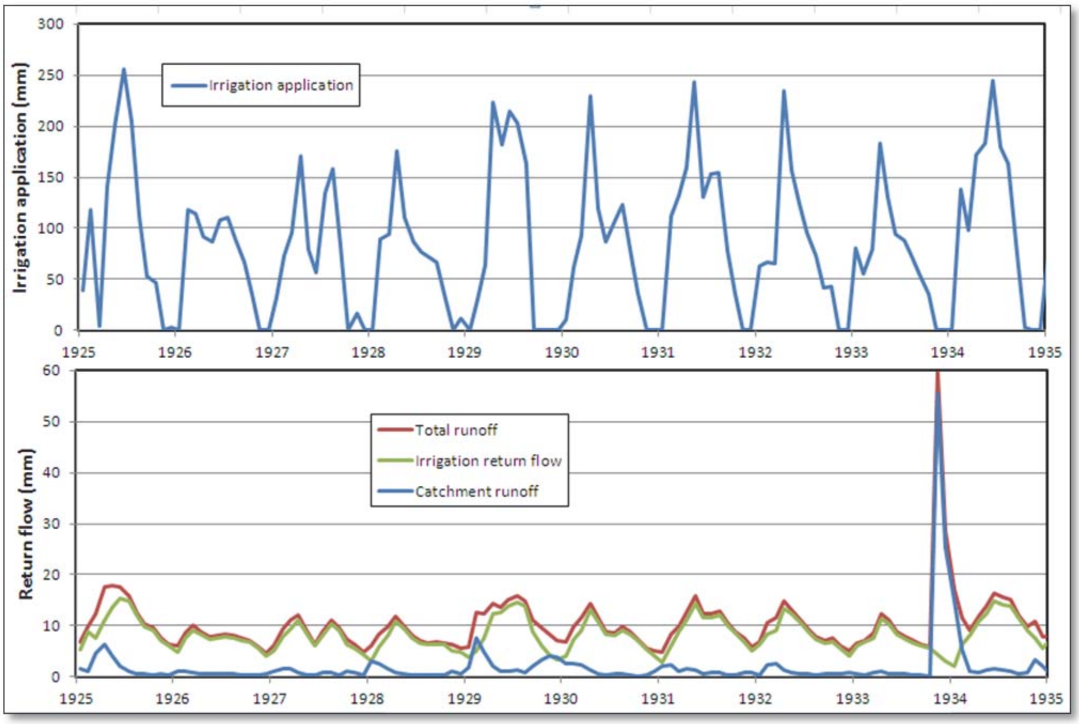


Figure 6.5: Simulated irrigation return flow

The reduction in irrigation return flow is evident during periods when the irrigation application declines to zero, which generally coincide with catchment runoff events such as the November 1933 flood which broke the 1930's drought. For this example the irrigation return flow was calibrated to be average 10% of the irrigation application.

Return flow from upper soil zone

The return flow from the upper soil moisture storage zone can include the enhanced flow associated with under drains that are frequently installed to ease the build-up of salts in the root zone of heavier soils. This return flow is calculated as a proportion of QIOUT:

$$QUP = QIOUT \times RRPRFU \qquad (6.38)$$

Where:

QUP = Irrigation return flow from upper soil moisture storage zone (10^6 m^3),

RRPRFU = Proportion of return flow from upper soil zone (-)

Return flow from lower soil zone

The lower zone return flow attributable to irrigation application, QLOW (10^6 m³), is given as:

$$\mathrm{QLOW} = \mathrm{QIOUT} \times \mathrm{RRPRFL} \quad (6.39)$$

Where

QLOW = Irrigation return flow from lower soil zone (10^6 m^3),
RRPRFL = Proportion of return flow from lower soil zone (-)

The lower zone storage is important because this storage can bring about a long-term delay in the impact of irrigation schemes on river water quality. A case in point is the Vaalharts irrigation scheme, where the gradual build-up of salts in the irrigated lands took from the mid-1930s to the mid-1970s before the large scale installation of under drains was justified. Similar effects where observed at the massive Indus River irrigation scheme, which was commission at about the same time. Not only must this storage zone account for the groundwater directly under the irrigated lands and above the river level, it also needs to account for the transmission zone between lower edge of the irrigated land and the receiving stream. For this reason the storage depth, RRHSL (mm), can be quite deep.

Loss to deep seated groundwater

Part of the irrigation application can cause enhanced loss of water to deep-seated groundwater. This is particularly important for semi-arid and arid areas, which apply to many of the South African irrigation schemes. In such areas the regional water table is often lower than the invert level of local steams. This means that under normal conditions the percolation to groundwater is effectively lost. Irrigation activities have the effect of generating an artificial but sustained hump in the groundwater beneath and adjacent to the irrigated area. This causes an irrigation return flow to reach the stream (e.g. the QUP and QLOW components in Figure 6.4). However, there is also a net loss of water to the original widespread deep-seated groundwater table adjacent to the irrigated area. Numerous modelling studies showed the importance of taking this into consideration. For example a study of the Vaalharts irrigation scheme showed that 65% of the salt contained in the irrigation water supplied to the scheme between 1935 and 1990 had not left via return flow to the Harts River (Herold and Bailey, 1996). Similar effects have been found in numerous studies. This was handled in the original WQT irrigation model using parameter RRPSL. However, the value of parameter RRSCF also had to be carefully adjusted to prevent illogical sub-surface salt concentrations from occurring in the upper and lower soil zones. The modifications result in a much more stable solution.

The deep percolation water loss is calculated as:

$$\mathrm{QDEEP} = \mathrm{QIOUT} \times \mathrm{RRPDL} \quad (6.40)$$

Where

QDEEP = Deep percolation loss to deep-seated groundwater (10^6 m^3)
RRPDL = Proportion of outflow from lower zone giving rise to deep percolation

The loss to deep-seated groundwater thus varies in proportion to the return flow to the surface water but is in addition to it.

The total evapotranspiration loss from the upper soil moisture zone, E (mm), is assumed to bear a linear relationship with the soil moisture storage:

$$\mathrm{E} = (0.5\times(\mathrm{S1}+\mathrm{S2})-\mathrm{RRMIN})\times\mathrm{PE}\times\mathrm{APANF}/(\mathrm{RRHMAX}-\mathrm{RRHMIN}) . (6.41)$$

Where APANF is the monthly pan factor to convert A-pan evaporation to lake evaporation. S2 is solved from equations (6.36), (6.37), (6.38), (6.39), (6.40) and (6.41) as:

$$S2 = \frac{S1\times(1-0.5F) + RRHMIN\times F + RAIN + QIS\times\frac{1000}{AIRR_i}}{(1+0.5\times F} \ldots\ldots\ldots\ldots\ldots\ldots (6.42)$$

Where:

$$\mathrm{F} = \mathrm{RRLF}\times(\mathrm{RRPRFU}+\mathrm{RRPRFL}+\mathrm{RRPDL}) + \mathrm{PE}\times\mathrm{APANF}/(\mathrm{RRHMAX}\text{-}\mathrm{RRHMIN}) \ldots\ldots (6.42a)$$

If the ending storage given by Equation (6.42) is less than RRHMIN, then set:

$$\mathrm{DIN} = \mathrm{DIN} - (\mathrm{RRHMIN} - \mathrm{S2}) \ldots\ldots (6.43a)$$

$$\mathrm{S2} = \mathrm{RRHMIN} \ldots\ldots (6.43b)$$

The implicit assumption is that when the storage declines to this value the irrigation evapotranspiration demand will be reduced accordingly due to the unavailability of water in the soil profile. Typically this condition could arise when the irrigation supply, QIS, remains lower than the net crop demand due to supply constraints. In effect the irrigation supply is then too small to sustain the irrigated area.

An upper limit to the storage is also set. This is done to prevent unrealistically high storages from occurring during particularly wet periods.

$$\mathrm{QE} = \mathrm{S2} - \mathrm{RRHMAX} \ldots\ldots (6.44a)$$

$$\mathrm{S2} = \mathrm{RRHMAX} \ldots\ldots (6.44b)$$

Where

QE = Additional evaporation loss (mm)
RRHMAX = Maximum permissible storage depth in upper soil zone (mm).

Under such conditions the enhanced catchment sub-surface flow is already accommodated by the SW module's surface and sub-surface flow components. For this reason the excess water (QE) is taken as evaporation, since to include it in the return flow would duplicate the surface runoff component. It is recommended that RRHMAX should be set at the soil moisture storage capacity. For a well-balanced irrigation scheme this would result in a relatively constant irrigation return flow, which would drop significantly below the optimum target level during periods of supply restriction, or if the irrigation stops for a few months while the land lies fallow. High S2 values could also occur when the irrigation efficiency is low, since under such conditions the quantity of water applied to the land would substantially exceed the crop demand plus return flow. The assumption in such cases is that the surplus water will result in enhanced evapotranspiration loss. This is a reasonable assumption since water logging often accompanies over-irrigation due to inefficient practices. In the salinity modelling this will automatically reflect in increased soil salinity due to the increased evapotranspiration loss. This is also consistent with over-irrigation.

The return flow resulting from the irrigation application is then calculated using Equations (6.37), (6.38) and (6.39).

The method of application ensures that the irrigation return flow cannot exceed a fixed proportion of the applied irrigation water, and can decline below this when there is insufficient irrigation application to meet the crop demand. The enhanced groundwater flow attributable to normal catchment processes derived from the SW module is superimposed on this.

Irrigation return flow associated with catchment runoff

In this approach the catchment rainfall-runoff module (the Salt Washoff (SW) module in the WQT model) is assumed to provide the unit surface and groundwater flow associated with the rainfall on the irrigated portion of the catchment. An improvement here is that the SW module, which reads in a previously prepared catchment runoff file, uses algorithms to split the hydrograph into groundwater/interflow and surface flow runoff components. The surface runoff component of the catchment runoff rising from the irrigated portion of the catchment, QSI (10^6 m³), is assumed to simply enter the irrigation module return flow route without passing through the irrigated soil and is calculated as:

$$\mathrm{QSI} = \mathrm{QS} \times \mathrm{AIRR_i} / \mathrm{ACATP} \quad \ldots\ldots \quad (6.45)$$

Where:

QS = Pervious catchment surface flow simulated by Salt Washoff module (10^6 m^3)

ACATP = Pervious catchment area calculated in Salt Washoff module (km^2)

The groundwater flow component, QG (10^6 m³), from the irrigated portion of the catchment is assumed to enter the irrigated soil and exit as part of the simulated return flow. This is an approximation to mimic the groundwater flow associated with normal catchment processes:

$$\mathrm{QGI} = \mathrm{QS} \times \mathrm{AIRR}_i / \mathrm{ACATP} \quad (6.46)$$

QGI is the minimum irrigation return flow, to which is added the contribution associated with the irrigation application. This is a contra item since it is entered into the irrigated land and is returned back to the surface runoff. Hence, it is flow neutral and does not affect the pervious catchment runoff entered as part of the SW module input.

In addition, the groundwater flow/interflow portion of the catchment runoff is also routed through the irrigated land to account for the normal rainfall-runoff processes. None of this water is lost, since the end result should preserve the flows originally modelled by the SW module.

$$\mathrm{QGIU} = \mathrm{QGI} \times \mathrm{RRPRFU} / (\mathrm{RRPRFU} + \mathrm{RRPRFL}) \quad (6.47)$$

Where QGIU (10^6 m³) is the portion of the catchment groundwater flow/interflow leaving the upper soil zone.

The portion leaving via the lower soil zone is given by:

$$\mathrm{QGIL} = \mathrm{QGI} - \mathrm{QGIU} \quad (6.48)$$

Where QGIL (10^6 m³) is the portion of the catchment groundwater flow/interflow leaving the Lower soil zone.

Total irrigation return flow

The total return flow to the irrigation return flow route is then given as:

$$\mathrm{QIR} = \mathrm{QTLR} + \mathrm{QEND} + \mathrm{QUP} + \mathrm{QLOW} + \mathrm{QGI} + \mathrm{QSI} \quad (6.49)$$

Where QIR (10^6 m³) is the total flow to the irrigation return flow route.

7 GROUNDWATER (WITH 2005 ENHANCEMENTS) PITMAN MODEL VERSION 3 HUGHES (D A HUGHES, IWR, RHODES UNIVERSITY AND R PARSONS, PARSONS AND ASSOCIATES).

For both the Hughes method (this section) and the Sami method (refer to section G), groundwater modules have been designed to quantify the groundwater-surface water interaction at a quaternary catchment scale and have not been designed to quantify groundwater resources per se. At the quaternary catchment scale, it is necessary to simplify the use of some groundwater parameters such as transmissivity which could differ quite considerably from the stream bed to the rest of the quaternary catchment. For this reason, groundwater-surface water interactions at a scale smaller than quaternary catchment or at a river reach scale are more appropriately dealt with using existing finite element and finite difference models , for example FeFlow and Modflow.

7.1 Introduction

The first version of the revised Pitman model with more explicit ground water interaction routines was published in the Hydrological Sciences Journal during 2004 (Hughes, 2004). The original model focussed on the recharge and ground water discharge (to streamflow) components and assumed that the ground water level was always above the channel (or at the same level) The model has now been through several testing phases and development iterations to account for other processes and therefore should be applicable to more catchment situations than the first version.

The additional components focussed on allowing for situations where the ground water 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 ground water 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 these parameter estimation approaches are based on a data set of ground water variables compiled by Conrad (2005). These were supplied as integrated values for all the quaternary catchments in the country.

7.2 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 7.1).

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 7.1).

$$\mathrm{RE} = \mathrm{GW}\,\{(\mathrm{S}\text{-}\mathrm{SL}) \,/\, (\mathrm{ST}\text{-}\mathrm{SL})\}^{\mathrm{GPOW}} \qquad (7.1)$$

This function has remained the same throughout all the development phases.

7.2.1 Recharge calibration principles

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 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 ground water 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.

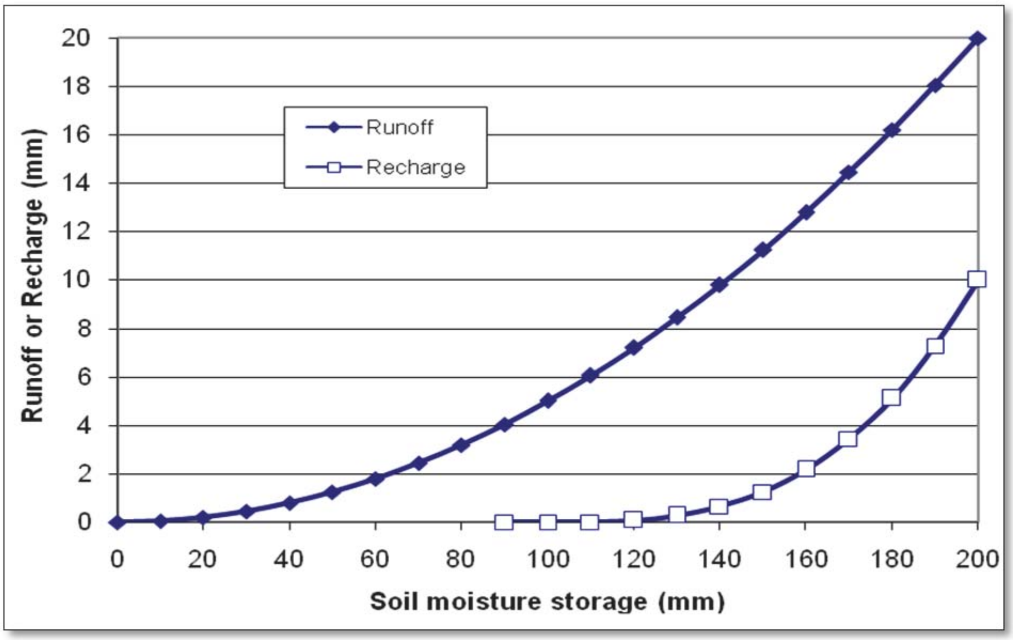


Figure 7.1: Illustration of the original soil moisture runoff function

Figure 7.1 has parameters ST = 200, SL = 0, FT = 20 and POW = 2 and the additional recharge-moisture state relationship has parameters SL = 100, GW = 10 and GPOW = 3. The Conrad (2005) database provides three estimates of recharge:

- GRAII derived from a DWAF Groundwater Resources Assessment Phase II project;
- Outputs based on work done by Karim Sami and
- Outputs based on estimates from the DWAF, RDM office.

In general terms the first estimate is normally the highest and the second the lowest. Initial tests of the Pitman GW model suggest that recharge values close to the Sami estimates, but normally higher, are the most appropriate. 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.

7.3 Ground Water Discharge to Streamflow

7.3.1 Geometry of the ground water store

The first principle that had to be established was to determine the approach to the water balance within the ground water storage zone and therefore what 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 7.2). Drainage is assumed to be 1-dimensional for simplicity. The determination of the number, length and width of the drainage slopes is 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 actively flowing 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:

$$\text{Total channel length} = \text{Drainage density} \times \text{Area} \tag{7.2}$$

The ratio of catchment width/length is assumed to be related to Drainage density as follows:

$$\text{Width} = \text{Length} \times 2.0 \times \text{Drainage density} \tag{7.3}$$

Therefore:

$$\text{Length} = \text{SQRT}(\text{Area} / (2 \times \text{Drainage density})) \tag{7.4}$$

By definition (and from Figure 7.2):

$$\text{No. drainage slopes} = 2.0 \times \text{Drainage density} \times \text{Area} / \text{Length} \tag{7.5}$$

The number of drainage slopes is equal to 2 × number of channels, however Equation 7.5 has to be corrected to generate an even integer number of drainage slopes, each of which has a width given by:

$$\text{Drainage width} = \text{Width} / \text{No. of drainage slopes} \tag{7.6}$$

Figure 7.3 illustrates the situation for a single drainage slope 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:

$$\text{‘Wedge’ volume} = (\text{Drainage width})^2 \times \text{Gradient} \times \text{Drainage length} / 2 \tag{7.7}$$

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

$$\text{Volume of water in ‘wedge’} = \text{‘wedge’ Volume} \times \text{Storativity} \tag{7.8}$$

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

$$\text{Discharge} = \text{Transmissivity} \times \text{Gradient} \times \text{Time step} \times \text{Channel length} \tag{7.9}$$

Additional changes (for version 3) involved the addition of abstraction routines and channel transmission losses (i.e. channel flow contributions to ground water). 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, 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) up for the two slope components. This means that the geometry of the two ‘wedges’ of ground water are estimated separately during each time interval. The process within each model iteration step (4 per month) is as follows:

- The recharge is calculated and the associated volume of water added to the upper and lower wedge storage volumes;
- The previous steps gradient is 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 ground water 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 ground water and any abstraction losses from ground water;
- 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) and
- 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.

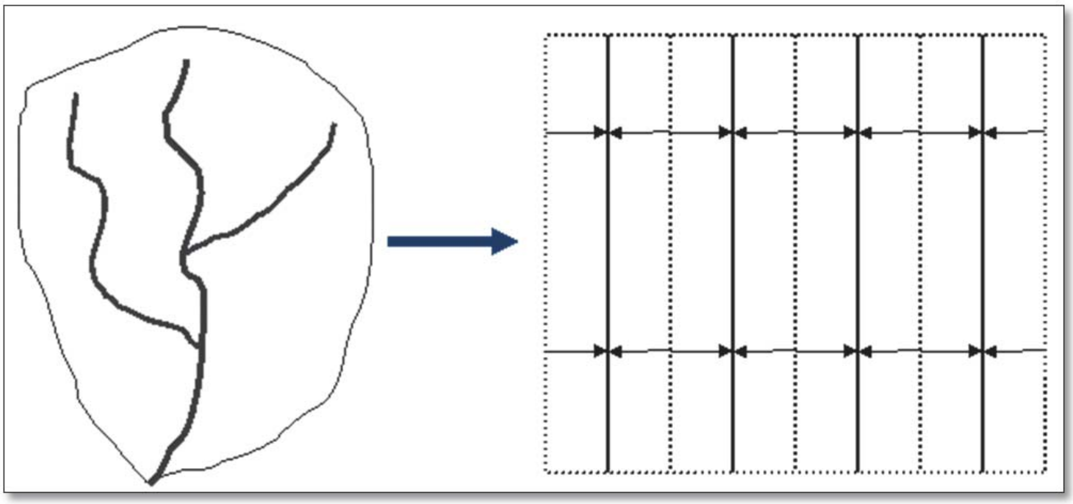


Figure 7.2: Conceptual simplification of drainage in a basin for a drainage density of 4/SQRT(Area)

Note: The solid lines are channels, dashed lines are drainage divides and arrows show drainage directions). There are 8 drainage slopes.

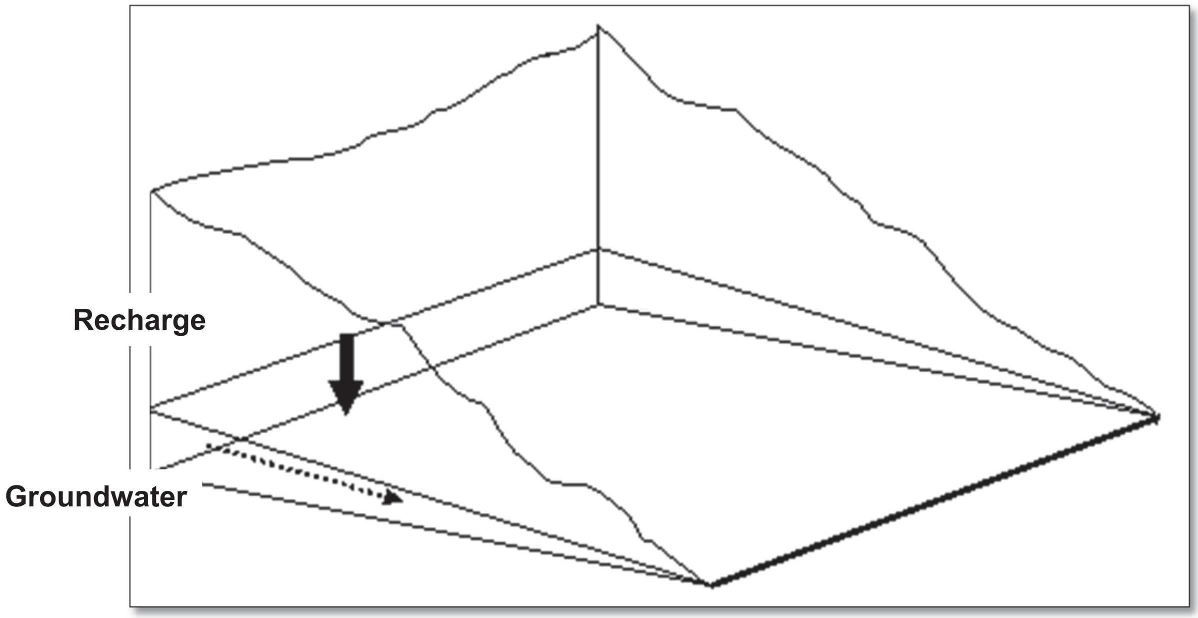


Figure 7.3: Illustration of a single drainage slope element

Note: 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.

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. 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 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 and
- lower drainage density, less outflow.

There is no longer a need for a ground water lag routine (using parameter GL), as the new ground water function also acts as a routing reservoir. An unrelated development, replaced GL with a CL parameter (channel routing coefficient) and introduced a channel routing component based on the Muskingum equation. However, this is only used for very large catchments (> 10 000 km^2), where attenuation through a single sub-catchment reach on a monthly time-scale is likely to be significant.

Once the new model was coded several checks were undertaken to ensure that a water balance was achieved. This is essentially straightforward as the main water balance issues are confined to the surface storage and the ground water ‘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 ground water and surface water divides of a basin are not the same and regional ground water 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 ground water 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 run twice. The starting gradients (upper and lower slope elements) in the first run is the regional ground water 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.

7.3.2 Riparian losses to evapotranspiration

It has been assumed that ground water can be subject to evapotranspiration losses close to the channel margin (either through use by riparian vegetation, or through evaporation from channel beds and banks). A model parameter has been added and is referred to as the Riparian strip factor. 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) has been 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 ground water is considered to be inaccessible to all ground water 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:

$$\text{GW depletion factor} = \text{gradient at RWL} - \text{current gradient}) \;/\; \text{gradient at RWL} \;\ldots\ldots\; (7.10)$$

Evapotranspiration losses are reduced by this depletion factor (see Eq. 7.11). If there is a positive value for ground water discharge to the channel, this is first reduced by the evapotranspiration losses and if there are still losses to account for, the ground water volume (and hence the gradient) is reduced.

$$\begin{aligned}\text{Evaporation losses} = {} & \text{Drainage Width} \times \text{Net Evaporation} \times \text{Riparian strip factor} \times \\ & \text{Depletion Factor} \;\ldots\ldots\; (7.11)\end{aligned}$$

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).

7.3.3 Discharge to downstream catchments

A regional ground water 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. 7.9) is used:

$$\text{Downstream outflow} = \text{Transmissivity} \times \text{Regional gradient} \times \text{Time step} \times \text{slope width} \quad (7.12)$$

The total outflow for a sub-catchment would then be the result of equation 7.11 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. 7.10) when the lower slope element gradient is negative.

Previous comments about the lack of correspondence between the surface and sub-surface 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.

7.3.4 Parameter value estimation

In summary the following new parameters have been added:

- transmissivity;
- storativity;
- drainage density;
- regional GW drainage slope;
- rest water level and
- riparian strip factor (% of slope width).

Transmissivity and storativity can be taken from the existing database of ground water 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 the interpolated transmissivity values appear to be 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 ground water 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 ground water 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 Conrad (2005) database were greater than 1 (in other cases the GW drainage slope was taken as the catchment average slope/100:

$$\text{Regional GW drainage slope} = (\text{catchment average slope})^{0.05}/100 \qquad (7.13)$$

The rest water level parameter can be taken from the existing database of ground water 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 ground water depletion factor calculation.

7.4 Channel Losses and Ground Water Abstractions

The final changes incorporated into version 3 of the model involved the addition of abstraction routines and channel transmission losses (i.e. channel flow contributions to ground water). 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 avid 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 that the two will give almost identical results when there are no abstractions and channel losses.

7.4.1 Channel transmission losses

It was recognised that when the ground water 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 ground water 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 7.4):

If $\mathrm{Q/MAXQ} < 0.3$

$$\mathrm{TLQ} = 0.5 \times (\tanh(10 \times (\mathrm{Q} / \mathrm{MAXQ} - 0.2)) + 1.0) \quad (7.14)$$

If $\mathrm{Q/MAXQ} \geq 0.3$

$$\mathrm{TLQ} = 0.5 \times (\tanh(2.5 \times (\mathrm{Q} / \mathrm{MAXQ} - 0.2)) + 1.0) \quad (7.15)$$

A further variable (TLG – see Figure 7.5) 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 $\mathrm{Gradient} < 0.7 \times \mathrm{RWLGrad}$

then $$\mathrm{TLG} = \mathrm{TLGMax} \quad (7.16)$$

If $\mathrm{Gradient} \geq 0.7 \times \mathrm{RWLGrad}$

then $$\mathrm{TLG} = \mathrm{TLGMax} \times (\mathrm{Gradient} / (0.7 \times \mathrm{RWLGrad}))^{0.25} \quad (7.17)$$

Channel loss (mm) is then the product of TLQ × TLG, which is removed from any available runoff and added to the lower slope component. The two exponents (0.4 and 0.25) 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.

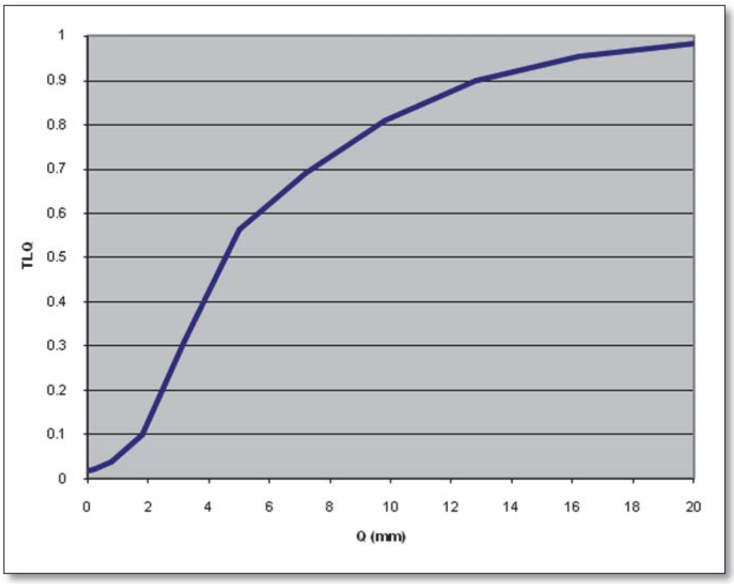


Figure 7.4: Shape of the power relationship between current month discharge (mm), relative to a maximum value (20 mm in this case) and a model variable, TLQ.

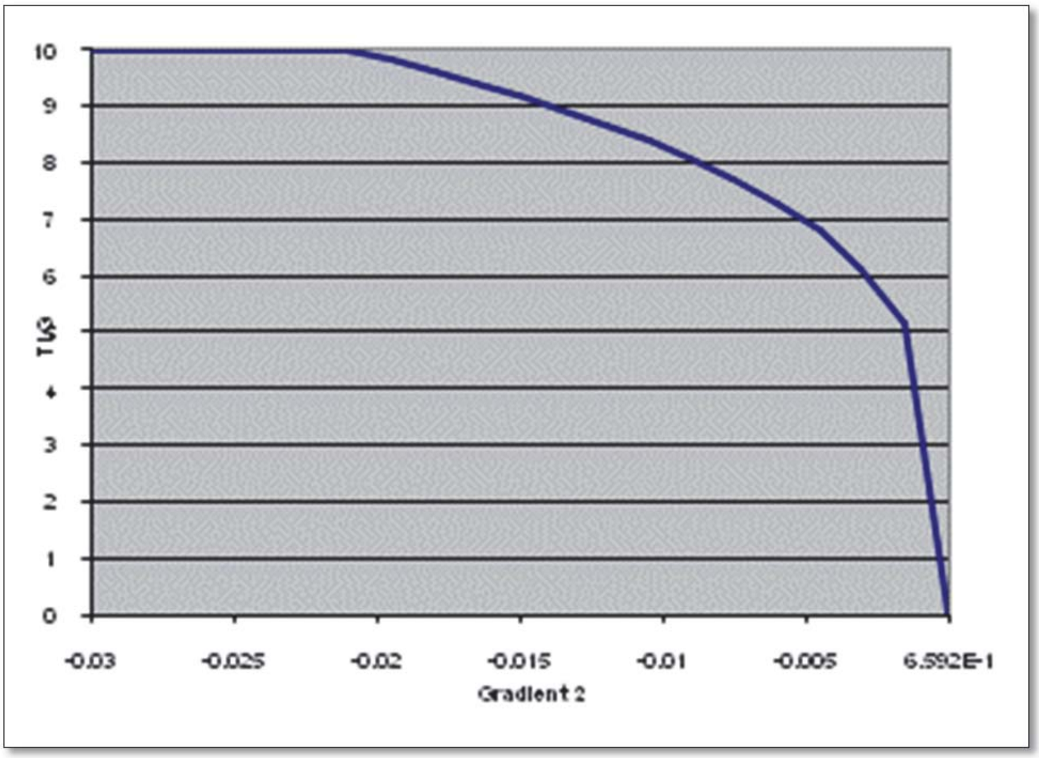


Figure 7.5: Shape of the power relationship between current downslope gradient and a model variable, TLG. The maximum value of TLG is defined by a model parameter.

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 7.16 and 7.17), except that TLGmax now represents a maximum channel loss from upstream inflow (in $m^3 \times 10^6$). TLGmax_Inflow is calculated from the TLGmax parameter for incremental flow using the following scheme:

$$\text{TLGmax\_Inflow} \quad = \text{TLGMax} \times (\text{MAXQ\_Inflow} \,/\, \text{MAXQ}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.18)$$

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 7.14 and 7.15 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 months 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) ground water 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 7.2. 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.

7.4.2 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 $m^3 \times 1000$ 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).

7.4.3 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 ground water 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 ground water.

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.

7.5 Some Initial Observations

Several test runs of the revised version of the model have been 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’ ground water 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 7.6 indicates what happens in the model when there are no abstractions and when abstractions of 5×10^6 m³ are included from the upper and lower slope elements. The parameters of the model have been set as Transmissivity = 8 m^2 d^{-1}, Storativity = 0.002. Recharge for the whole catchment is 8.487×10^6 m³ (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).

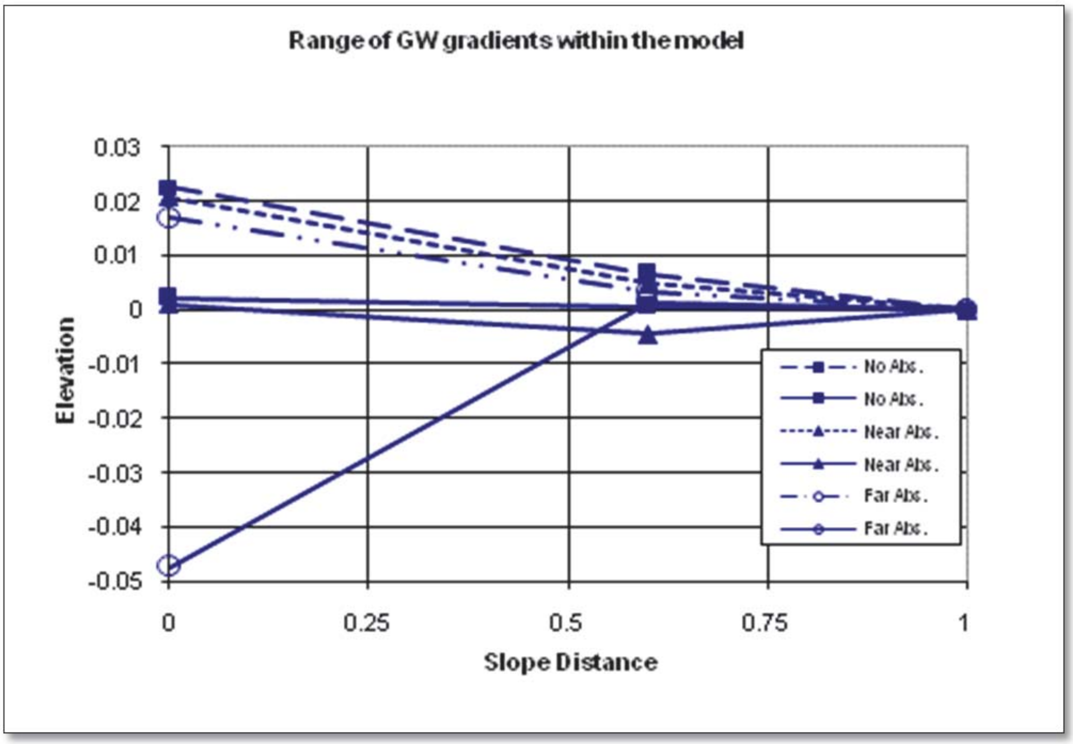


Figure 7.6: Range of gradients under model scenarios of no abstraction and abstractions from the upper (or 'Far') and lower (or 'Near') slope elements. The distance and elevation units are non-dimensional and expressed relative to the total slope length.

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 is simulating abstraction conditions that are assumed to be always present. It is not simulating 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 form 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 the Figure 7.7 shows the effects on the duration curves of GW discharge.

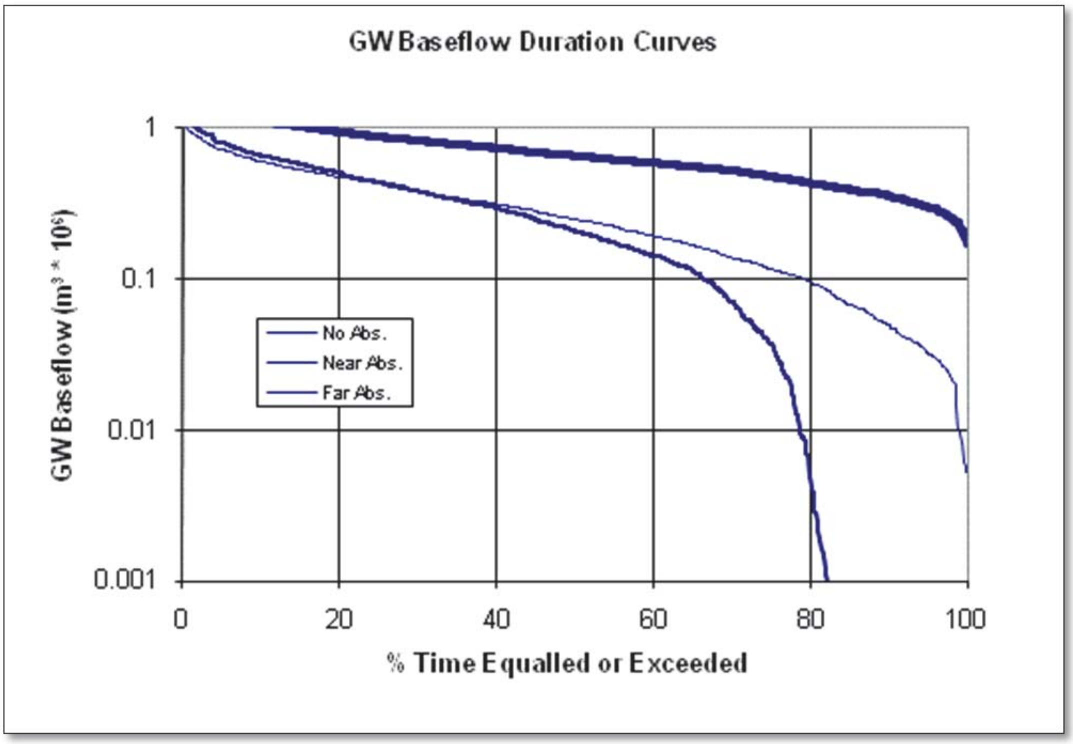


Figure 7.7: Duration curves of GW discharge to streamflow under the three scenarios of abstraction

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 T parameter is reduced (to say 4), and gets larger if the T is increased.

The GW parameters for X12A were modified slightly during a group workshop between 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 m³ out of a total mean annual runoff of 26.3×10^6 m³ (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 m³ abstraction from the lower slope element. Before channel transmission losses were introduced, the abstraction reduced the GW contribution to 1.06×10^6 m³ and the MAR to 22.36×10^6 m³. 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 m³ and the MAR reduced slightly to 22.33×10^6 m³ . 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 m³ with only 0.18 × 10^6 m³ being GW contribution. After introducing a TLGMax parameter of 20 mm, the MAR reduced to 21.62 × 10^6 m³ and the GW contribution increased to 0.41 × 10^6 m³, 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 m³ 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 m³. 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 appear 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 appear to be generating results that are intuitively realistic. However, guidelines for quantifying the new parameter values and re-evaluating some of the original parameter values still need to be established. It is also necessary to critically review the values of the two fixed-value power variables in the channel loss routines.

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Hughes, DA (2004) Incorporating ground water recharge and discharge functions into an existing monthly rainfall-runoff model. Hydrol. Sci. Journ. 49(2), 297-311.

Midgley, D. C., Pitman, W. V. & Middleton, B. J. (1994) Surface Water Resources of South Africa 1990, vols I–VI. Water Research Commission Reports nos 298/1.1/94–298/6.1/94, Pretoria, South Africa.

8 GROUNDWATER (WITH WR2005 STUDY ENHANCEMENTS) BY K SAMI –

8.1 Introduction

8.1.1 Applicable Documents

Project Charter – Groundwater Resource Assessment Phase II, DWAF, 2003

Groundwater-surface water interactions – Groundwater Resource Assessment Phase II Project 2003-150, Rep. 3Be, DWAF

8.1.2 Acronyms and Abbreviations

Acronym/Abbreviation	Definition
WSAM	DWAF Water Situation Assessment Model
NGDB	National Groundwater Database
WRYM	Water Resources Yield Model
WR90	Surface Water Resources of South Africa 1990
WR2005	Surface Water Resources of South Africa 2005
WRSM/Pitman	Revised version of the Pitman model utilised in WR90 and WR2005
DWAF	Department of Water Affairs and Forestry
WARMS	Water Use Licensing, Registration and Revenue Collection

8.2 Background

8.2.1 Background to the Project

Since the abstraction of groundwater may impact on the availability of surface water resources through baseflow depletion, the integrated and sustainable management and development of water resources requires an understanding of the interactions between groundwater and surface water.

In 2003 the DWAF embarked on the Phase II Groundwater Resource Assessment programme. The main objective of the programme was to develop methodologies and data that will support groundwater resource quantification per defined management unit. This programme was also tasked with supporting Integrated Water Resources Management, whose portfolio is to deliver relevant information on groundwater resources in support of Integrated Water Reserve Management.

The Phase II programme comprised 5 projects, of which Project 3B, Groundwater-Surface Water Interactions, was one. The objective of this project was to review methods to quantify groundwater-surface water interactions and to develop a generic algorithm that can be applied to estimate groundwater-surface water interaction nationally on a quaternary catchment scale.

Project 3B was divided into phases whereby:

- the international literature on assessing surface groundwater interactions would be reviewed;

- existing data sets available in South Africa would be identified;
- an algorithm to quantify interactions would be developed and
- a data base populated.

A methodology and algorithms were developed whereby the impacts on baseflow from groundwater abstraction and its proximity to river channels could be simulated. The methodology was incorporated into an MS-EXCEL environment. These algorithms were also coded into a multi worksheet MS-EXCEL data base set up by Quaternary catchment that was used to estimate interactions for over 1200 Quaternary catchments where baseflow occurs.

Subsequently, the software found application in simulating the potential impacts of groundwater abstraction on the time series of baseflow for use in systems models to determine the potential impacts on reservoir yields and resource reliability. This led to discussions on the potential incorporation of the methodology into systems models, such as the Water Resources Yield Model, which currently only consider surface water abstractions.

Modifications were also made to the software so that it could be incorporated into WR2005. The algorithms are currently being coded into the Pitman model in WR2005 in order to simulate baseflow nationwide.

In addition to preliminary nationwide estimates of groundwater baseflow per Quaternary catchment in GRA II, the model has so far been applied in the following cases:

- Schoonspruit Eye: To determine the impacts of groundwater abstraction on flow from the eye, for the Reserve determination, and for use in WRYM to determine modifications to the yield of Johan Neser dam (DWAF);
- Middle Letaba: To determine the impacts of groundwater abstraction on inflows to the Middle Letaba Dam (DWAF) and
- Klein Dwars: To determine impacts on inflows to De Hoop dam from a proposed wellfield for Amplats in the Klein Dwars alluvium (AMPLATS).

The following investigations are also in progress:

- Mhlutuze Basin: revised baseflow simulations for the revision of the systems analysis of the W10 basin (DWAF) and
- Mokolo Basin: revised baseflow simulations for the revision of the systems analysis of the Mokolo A42 basin (DWAF).

8.2.2 Review of Groundwater-Surface Water Interactions

Surface water and groundwater interactions can be classified as follows:

Those involving contributions to streamflow :

- interflow occurring from the unsaturated zone contributing to hydrograph recession following a large storm event;
- groundwater discharged from the regional aquifer to surface water as baseflow to river channels, either to perennial effluent or intermittent streams;

- seepage to permanent or temporary wetlands;
- seepage from or to reservoirs and lakes and
- discharge from perched water tables via temporary or perennial springs located above low permeability layers, which may cause prolonged baseflow following rain events, even when the regional water table is below the stream channel.

Those involving losses from streamflow :

- transmission losses of surface water when river stage is above the groundwater table in phreatic aquifers with a water table in contact with the river;
- transmission losses in detached rivers, either perennial or ephemeral, where the water table lies at some depth below the channel and
- induced recharge caused by pumping of aquifer systems in the vicinity of rivers causing a flow reversal.

Those involving both losses and gains to streamflow depending on Stage are:-

- transmission losses of a temporary nature, recharging bank storage in alluvial systems during high flows, which are subsequently released to the channel during low flows.

The exchange of water between the surface and subsurface is a function of the difference between river stage and aquifer head. The direction of exchange varies with hydraulic head; however, the rate of exchange is also dependent on permeability properties. Seasonal variations in head may cause changes from effluent (groundwater draining into stream) to influent (surface water contributes to groundwater) conditions when higher hydraulic pressures exist in the stream channel due to storm runoff.

The quantification of such interactions is necessary to avoid pitfalls such as double accounting of water resources. For example, hydrologists often consider baseflow as part of stream runoff, hence an allocatable surface resource. Geohydrologists often consider groundwater resources in terms of recharge, a large portion of which generates baseflow. Consequently, the simple addition of surface water runoff volumes and groundwater resources based on recharge (i.e. Harvest Potential) double accounts for the baseflow component.

The quantification of these processes is severely hampered by miscomprehension of the terminologies used by hydrologists, ecologists and geohydrologists. Streamflow originating from subsurface pathways and contributing to baseflow is often all termed groundwater by hydrologists and ecologists, as well as some geohydrologists, which may lead to conceptual misunderstandings since not all these pathways incur passage through the regional aquifer. Subsurface water which does not flow through the regional aquifer is not available to boreholes in terms of conventional groundwater resource assessment; hence a distinction needs to be made between baseflow originating from the regional aquifer and baseflow originating from other subsurface pathways.

Baseflow, as understood by ecologists and hydrologists, can be considered to consist of the portion of subsurface water which contributes to the low flow of streams. This can originate from either: i) the regional groundwater body (groundwater baseflow), that portion of the total water resource that can either be abstracted as ground water or surface water, or; ii) saturated soils, perched aquifers, high lying springs, excess recharge that is not accepted by the aquifer, processes that can be lumped as interflow.

In catchments with significant relief and geological heterogeneities, a large part of the baseflow fraction originates as interflow and never passes through the regional aquifer, and hence does not form part of the groundwater resources as considered in the concept of the groundwater Harvest Potential. Baseflow to maintain instream flows cannot, therefore, be simply attributed to discharge from the regional aquifers, since a large fraction could originate as interflow. The ecological significance of the regional aquifer when used as a groundwater resource would only be related to the connectivity of groundwater to the river reaches, and the degree to which the aquifer contributes baseflow. Groundwater abstraction may not impact at all on interflow from high lying springs, seeps, and perched water tables, hence would have no impact on the Ecological Reserve, or on the interflow component of baseflow in the river.

Similarly, groundwater baseflow cannot be simply equated to recharge, since a portion of recharge may be lost in steep areas before reaching the regional aquifer through seepage of percolating water in outcropping fractures, springs draining perched water tables, artesian springs, evapotranspiration, or losses to deep lying regional groundwater which discharges at a great distance from the point of recharge. For these reasons, groundwater baseflow is very often significantly less than recharge, and similarly Exploitation or Harvest Potential are also much less than recharge. Therefore, it is not the recharge term that is significant when quantifying discharge of subsurface water into streams; only the fraction that re-emerges as baseflow is significant.

Baseflow can be subdivided into: interflow not originating from the regional groundwater body and therefore not accessible by boreholes; and groundwater baseflow. Without a comprehension of such a distinction, the quantification of the impacts of groundwater abstraction cannot succeed. Only the portion of recharge re-emerging as groundwater baseflow can be impacted by abstraction. High lying perched springs would remain unaffected, unless land use or vegetation changes result in a reduction of springflow.

Many publications (i.e. Rushton & Tomlinson, 1979) note that baseflow during hydrograph recession is not linearly related to hydraulic conductance, and during periods of high recharge, leakage calculated by models using linear means is much greater than occurs in practice. This can be attributed to ignoring increased hydraulic resistance to flow as discharge increases. This suggests linear methods, as incorporated in MODFLOW, do not provide a suitable avenue for modelling interactions in systems where large flow fluctuations occur, as is South African rivers.

A more realistic approach to simulating interactions could be adopted by using non-linear equations whereby rapid increases in baseflow occur for small head changes when the head difference is small, but baseflow approaches some maximum value as the head difference becomes larger (Balleau, 1988).

Simulation of interactions is also relevant under conditions where groundwater abstraction takes place. The decline of water levels around pumping boreholes near surface water bodies creates gradients that capture some of the ambient groundwater that would have discharged as groundwater baseflow. At sufficiently high pumping rates these declines also induce flow out of the surface water body, a process known as induced recharge. Both these processes lead to streamflow depletion.

The dynamics of stream depletion is thoroughly explained by Sophocleous (2002). Under natural conditions, dynamic steady-state conditions exist whereby in wet years recharge exceeds discharge and in dry years the reverse take place. This results in a cycle of rising and falling aquifer water levels. Pumping upsets this principle and new equilibrium conditions are eventually reached by increasing recharge (through induced recharge) or decreasing discharge (baseflow depletion, reduced groundwater outflow from the catchment, or reduced evapotranspiration losses from groundwater due to a lowering of water levels). Once new equilibrium conditions are reached whereby pumping is balanced by baseflow depletion a water licence to abstract groundwater is equivalent to a right to divert streamflow. In general, the further away the abstraction point is from the river, the longer the time to achieve equilibrium conditions. However, until equilibrium is reached these two volumes are not the same and the difference results in aquifer storage depletion. Therefore groundwater abstraction **must** consider both aquifer storage depletion and baseflow depletion and abstractions must be allocated in terms of the portion that originates as aquifer storage and that which comes from streamflow depletion.

The length of time required for equilibrium to be reached between the surface water and groundwater flow depends on three factors: aquifer diffusivity, which is expressed as the ratio of aquifer storativity and transmissivity, the distance from the well to stream and the time of pumping. These are the three critical physical parameters affecting the impact of pumping on baseflows. In general, a tenfold increase in distance from a surface water course will result in a hundred fold increase in response time (Balleau, 1988). Recharge is unimportant in terms of the magnitude of the impact on baseflow; however, it limits the pumping rate since the portion originating from the aquifer cannot exceed recharge.

8.3 Proposed Methodology

8.3.1 Structure of methodology

A logical stepped methodology was developed in a MS-Excel environment that determines the impacts of abstraction on baseflow. The methodology has been extended since GRA II to use two types of data inputs: 1) River hydrograph from which baseflow is separated using a hydrograph separation (Method 1); 2) time series of the Pitman S variable (subsurface storage), from which recharge is generated (Method 2). The two methods differ in the manner in which interflow is calculated. The hydrograph separation approach infers interflow as the difference between baseflow from the hydrograph separation and calculated groundwater baseflow. Baseflow can never exceed the original hydrograph discharge. The Pitman S approach calculates both interflow and groundwater baseflow independently of the catchment hydrograph. This approach was developed to remove the subjective nature of hydrograph separations from the methodology, and to provide a direct link to the Pitman model.

The methodology is based on sequentially:

- either performing a hydrograph separation to separate groundwater baseflow (baseflow from the regional aquifer) and interflow (baseflow from perched aquifers) from storm runoff on a monthly time scale using WR90, observed flow data or a stochastic hydrograph;
- back calculating subsurface storage from the separated baseflow hydrograph to calculate a time series of recharge;
- or utilising the catchment soil moisture time series S generated by the WRSM/Pitman to calculate a time series of recharge;
- incrementing groundwater storage from recharge to a maximum aquifer capacity level, with any recharge in excess of aquifer capacity contributing to interflow;
- depleting groundwater storage by evapotranspiration and groundwater outflow to other catchments as a function of groundwater storage until static water level conditions are reached;
- calculating groundwater baseflow or transmission losses in a non-linear manner as a function of groundwater storage and runoff volume and
- depleting groundwater storage and groundwater baseflow due to abstraction as a function of aquifer diffusivity, time since pumping started, distance, and recharge.

The structure of the methodology is shown in Figure 8.1 and Figure 8.2 .

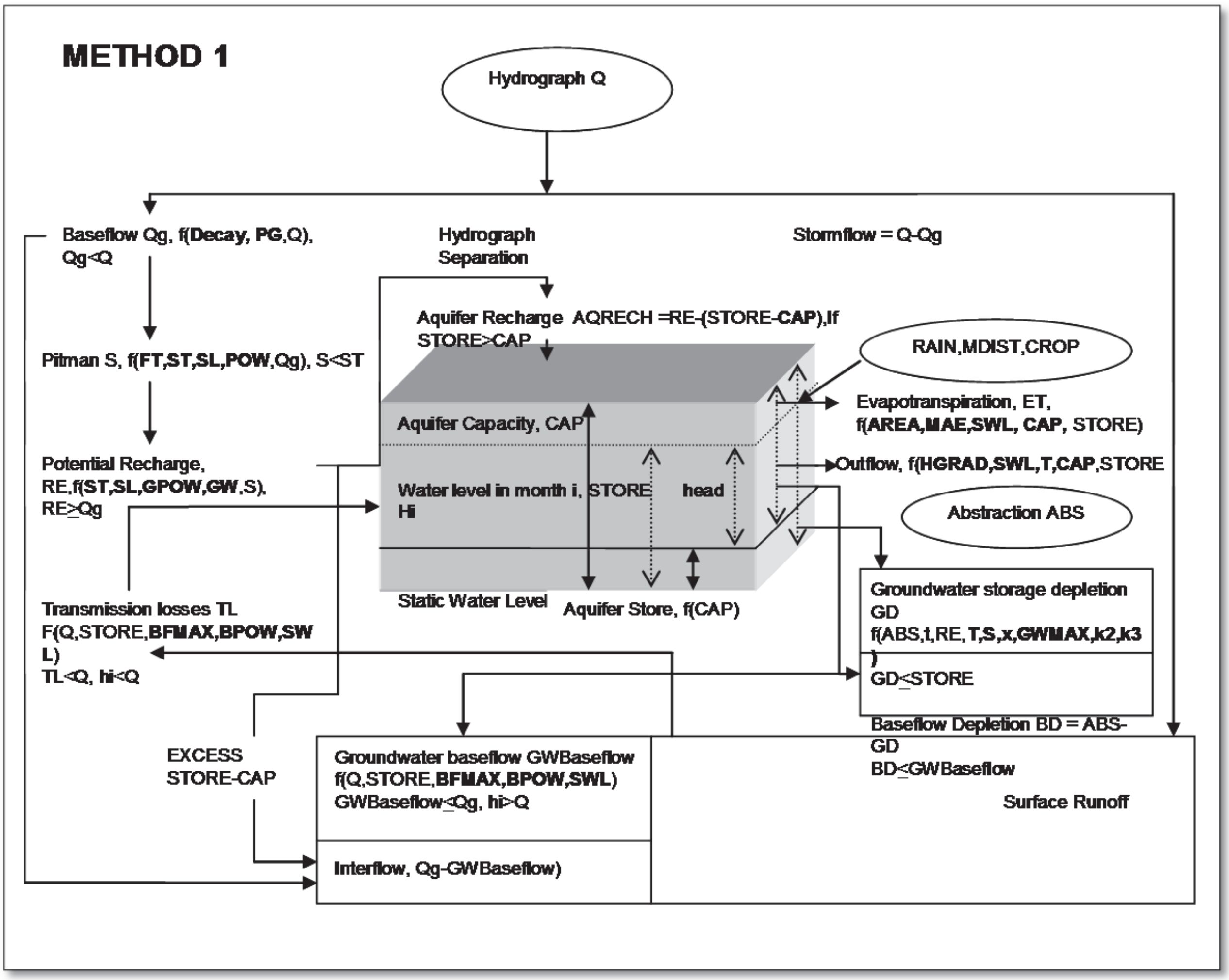


Figure 8.1: Structure of the interaction methodology (Method 1)

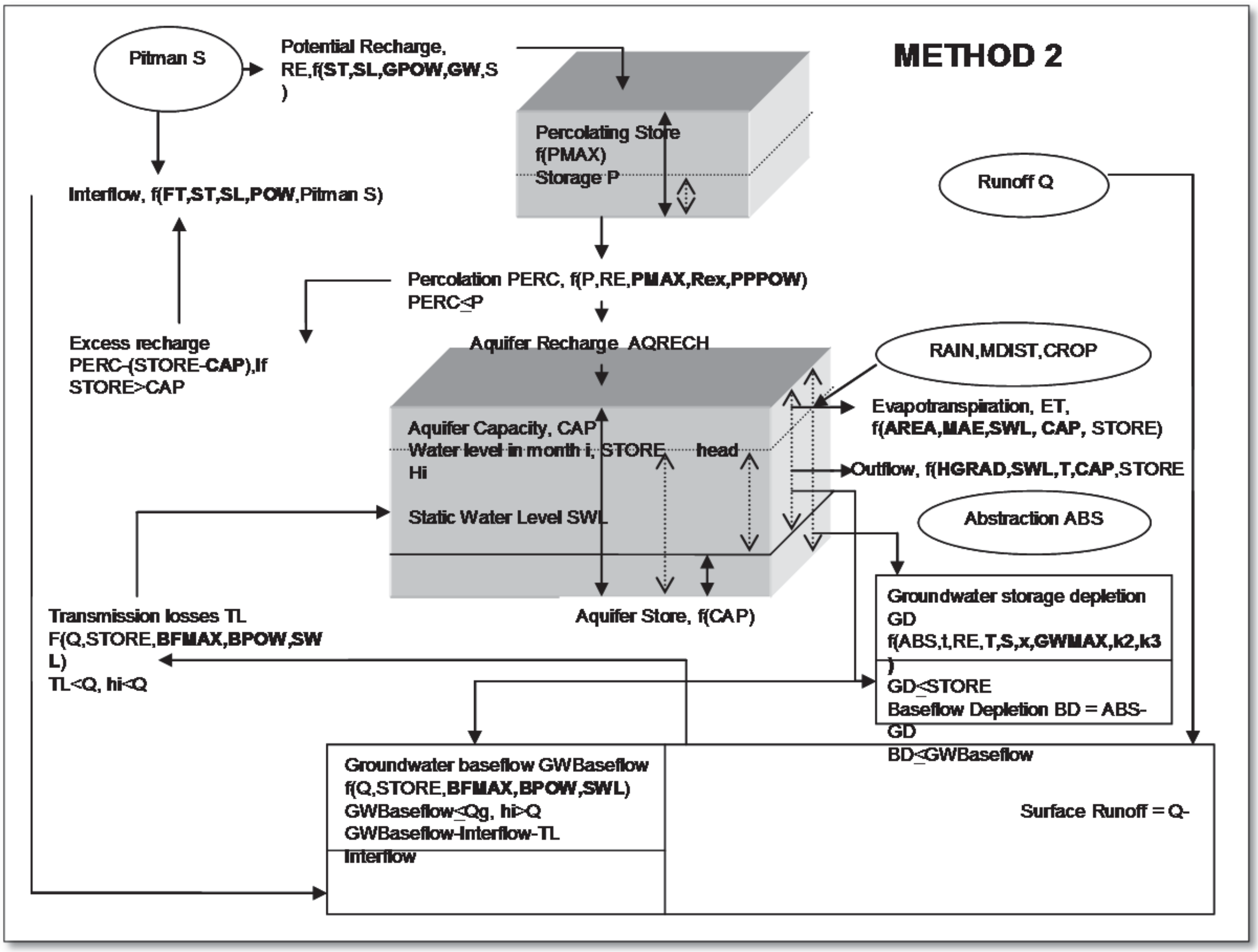


Figure 8.2: Structure of the new interaction methodology (Method 2)

8.3.2 Hydrograph Separation – method 1

Hydrograph separations are used only to derive a time series of soil moisture storage, which is calculated from baseflow, if this approach is selected.

The software is capable of directly reading monthly flow data in the WR90 format once imported into a spreadsheet. Flow is automatically plotted as a monthly hydrograph (Figure 8.2). A hydrograph separation is performed using the method of Herold (1980) to derive a time series of baseflow:

$$Q_{gi} = Q_{gi-1} \times \mathrm{Decay} + Q_{i-1} \times \mathrm{PG} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.1)$$

Where:

Q_g = variable of baseflow

Q_{i-1} = input data of streamflow where the subscripts i and i-1 refer to the current and preceding month

Decay = parameter of baseflow recession or decay factor ($0 < \mathrm{Decay} < 1$)

PG = parameter for baseflow growth (%).

Baseflow Qgi represents the combined effect of baseflow decay from the previous month (Qgi1 × Decay) and rainfall induced recharge (Qi-1 × PG), which includes interflow.

Parameters for PG and Decay are entered and adjusted to achieve a visual calibration. A monthly time series of baseflow is thereby generated. An error check is included to ensure that baseflow does not exceed total streamflow.

The parameter Decay can be calibrated by comparing simulated baseflow to total streamflow during the driest period on record to ensure that simulated baseflow does not exceed or is significantly less than streamflow. Subsequently, PG is calibrated so that the baseflow hydrograph rises sufficiently to equal streamflow following large storm events.
Results can also be calibrated against total baseflow volumes in the Situation Assessment Study of the Ground Water Resources of South Africa, or those in WSAM. The WSAM values produced by the Hughes SARES method are incorporated into the spreadsheet model via lookup tables based on Quaternary catchment number and can be used to assist with calibration.

Separations can also be undertaken on observed gauging weir data, or stochastic hydrographs used by the WRYM model.

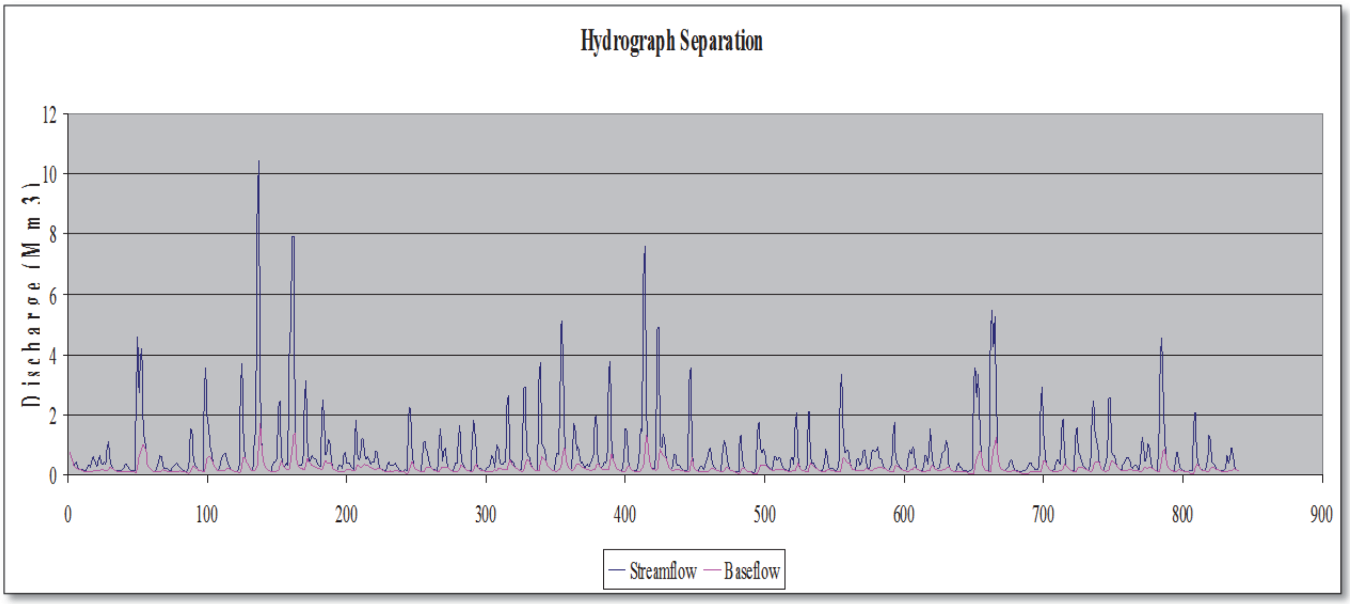


Figure 8.3: Hydrograph separation of the Klein Dwars Catchment, portion of B41G.

- Note:
  Area = 99 km², MARR = 8.38 Mm³/a, Baseflow = 2.57 Mm³ /a, DECAY = 0.75, GROWTH = 0.09

Once a hydrograph separation is obtained, the methodology calculates subsurface storage (Pitman S) by reverse engineering of the Pitman model (Coleman & Van Rooyen, pers. Comm., 2004):

$$Qg = FT\left(\frac{S - SL}{ST - SL}\right)^{POW} \qquad \text{........................} (8.2)$$

Where:

S = variable of Pitman subsurface moisture storage in mm for each month calculated from the time series of baseflow
Q = variable of baseflow obtained from the hydrograph separation
POW = parameter of the ratio of actual soil storage to storage capacity
SL = parameter of minimum soil moisture storage below which there is no runoff
ST = parameter of maximum soil moisture storage
FT = parameter of the maximum baseflow expressed as a depth

An error check exists to ensure that the calculated S variable cannot rise above ST. Parameters for SL, ST, FT and POW are obtained from the WR90 study.

8.3.3 Interflow from the Soil Zone – Method 2

If a time series of Pitman S is input rather than calculated from a hydrograph separation (method 1 using eq. 8.2), the methodology allows interflow to be generated from saturated soils using the Pitman algorithm (eq. 8.2).

If all baseflow is to be generated exclusively as interflow, then parameter values for SL , ST, FT and POW from WR90 are utilised. Since the Pitman model generates baseflow solely from eq. 8.2, if groundwater baseflow is to be generated parameters for SL and FT must be increased and reduced respectively from WR90 default values in order to reduce the interflow component (Figure 8.4). In general SL is increased to the point where no soil moisture is generated during dry periods (SL set to somewhat higher than S values during dry periods).

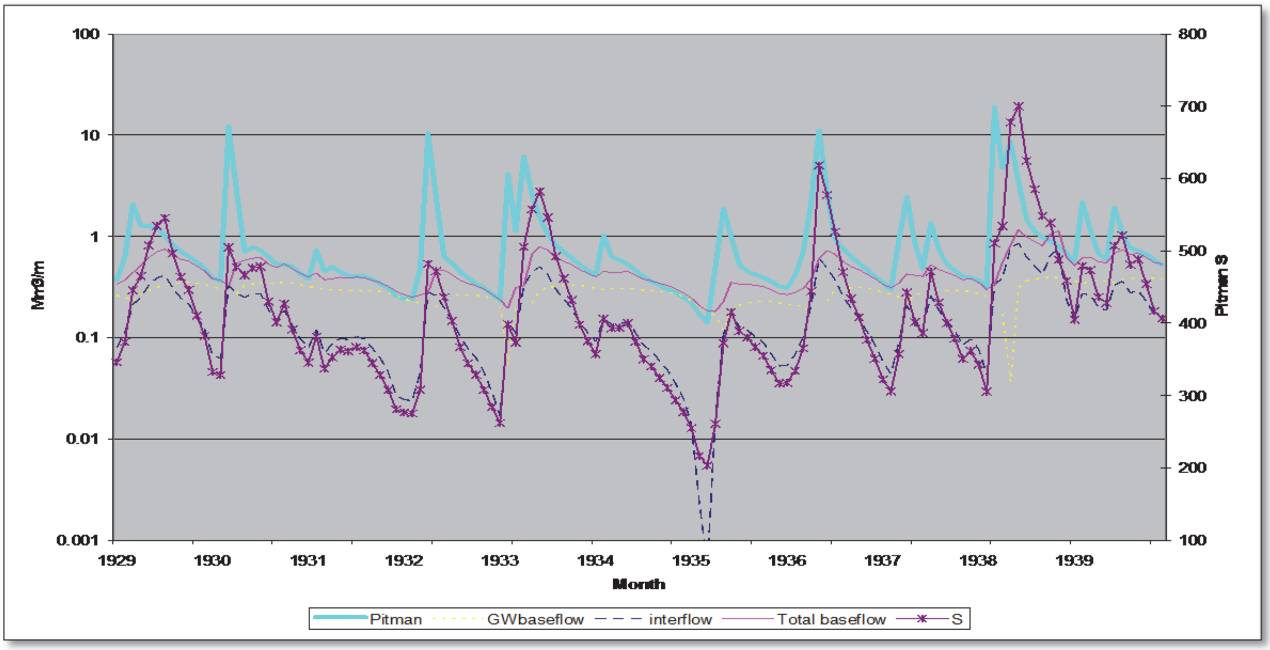


Figure 8.4: Hydrograph and Pitman generated using Pitman model for B82B S *

*Note: SL = 0, ST = 800, FT = 4.7 and POW = 2, and Interflow generated using SL = 190, ST = 800, FT = 3 and POW = 2

8.3.4 Estimation of Recharge – Methods 1 and 2

Once soil moisture is calculated, or input from the Pitman model, monthly recharge is calculated using the method proposed by Hughes (2004):

$$RE = GW\left(\frac{S - SL}{ST - SL}\right)^{GPOW} \quad \ldots\ldots (8.3)$$

Where

RE = variable of potential recharge (mm)

GW = parameter of maximum recharge in mm at maximum soil moisture (ST)

S = input data of soil moisture in mm

SL = parameter of soil moisture threshold below which there is no recharge

GPOW = parameter of the storage-recharge relationship

The SL parameter controls the soil moisture threshold below which there is no recharge. The GW parameters controls the rate of recharge and the GPOW parameter can be considered to conceptually represent the changing recharge contribution area with respect to soil moisture status. A GPOW of 1 implies linearity between soil moisture status and recharge area.

Parameters for GW and GPOW could either be calibrated to achieve a fit with long term mean annual recharge measurements obtained from other methods, or initially parameters similar to POW and FT could be selected, since the parameters have similar bases. GPOW would lie between 1-3. Parameter values are regional in nature and have been found to need little or no calibration between Quaternaries with similar conditions.

Using method 1, GPOW is kept equal to Pitman POW and GPOW lies from 0-20% higher than POW. Using method 2, GPOW is lowered or GPOW increased relative to the Pitman default parameters.

The output of the algorithm is a monthly time series of recharge. In method 1, since the Pitman S variable and recharge are generated from the hydrograph, recharge is lagged according to the lag in the hydrograph relative to rainfall. Recharge is therefore input directly into the aquifer (4.5).

In method 2, recharge and Pitman S are not lagged, hence recharge is directly related to monthly rainfall. As a result, the monthly recharge leaving the soil zone varies between methods 1 and 2. This difference may be significant in aquifers where a significant lag time exists between rainfall generating recharge events and the baseflow hydrograph (Figure 8.5).

If recharge from method 2 were input directly to the regional aquifer, method 2 could generate large variations in groundwater baseflow. Recharge from method 2 is therefore attenuated to account for natural lags that occur due to the percolation of water from the soil to the aquifer. Attenuation is accomplished through a storage that conceptually represents the percolating zone between the soil and aquifer. Recharge is added to this zone, and then released to the aquifer at a slower rate (4.6).

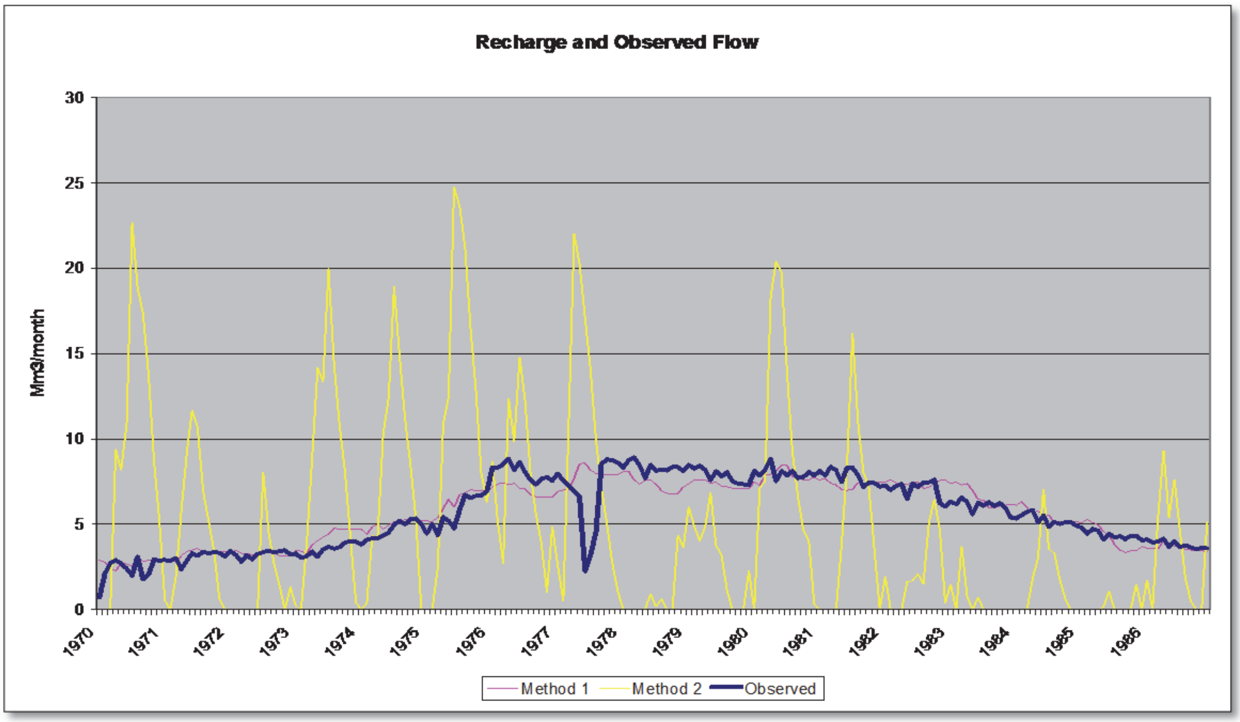


Figure 8.5: Recharge hydrograph relative to groundwater discharge from the Schoonspruit eye

*Note: For method 1 GW = 12, GPOW = 2, ST = 600, SL = 0 and recharge = 39 mm/a; Method 2, GW = 35, GPOW = 1, ST = 600, SL = 220 and recharge = 39 mm/a.

8.3.5 Groundwater Storage Increments from Recharge – Method 1.

Recharge from soil moisture is incremented directly to aquifer storage STORE, if the aquifer is not full (aquifer capacity CAP). If the aquifer is full, excess recharge above aquifer capacity is dumped to interflow and does not increment groundwater storage. As a result, aquifer recharge may be somewhat less than potential recharge calculated by eq. 8.3, and pumping, by depleting the groundwater storage, may increase actual direct recharge up to the potential recharge figure. A time series of aquifer storage is thereby generated (Figure 8.6).

Aquifer capacity is calculated as the product of parameters for aquifer thickness and storativity.

Aquifer recharge is calculated as potential recharge minus excess recharge, which is assumed lost to interflow:

If STORE>CAP then

$$AQRECH = RE - (STORE - CAP) \qquad (8.4)$$

Where:

STORE = variable of groundwater storage
CAP = parameter of aquifer capacity
AQRECH = variable of aquifer recharge

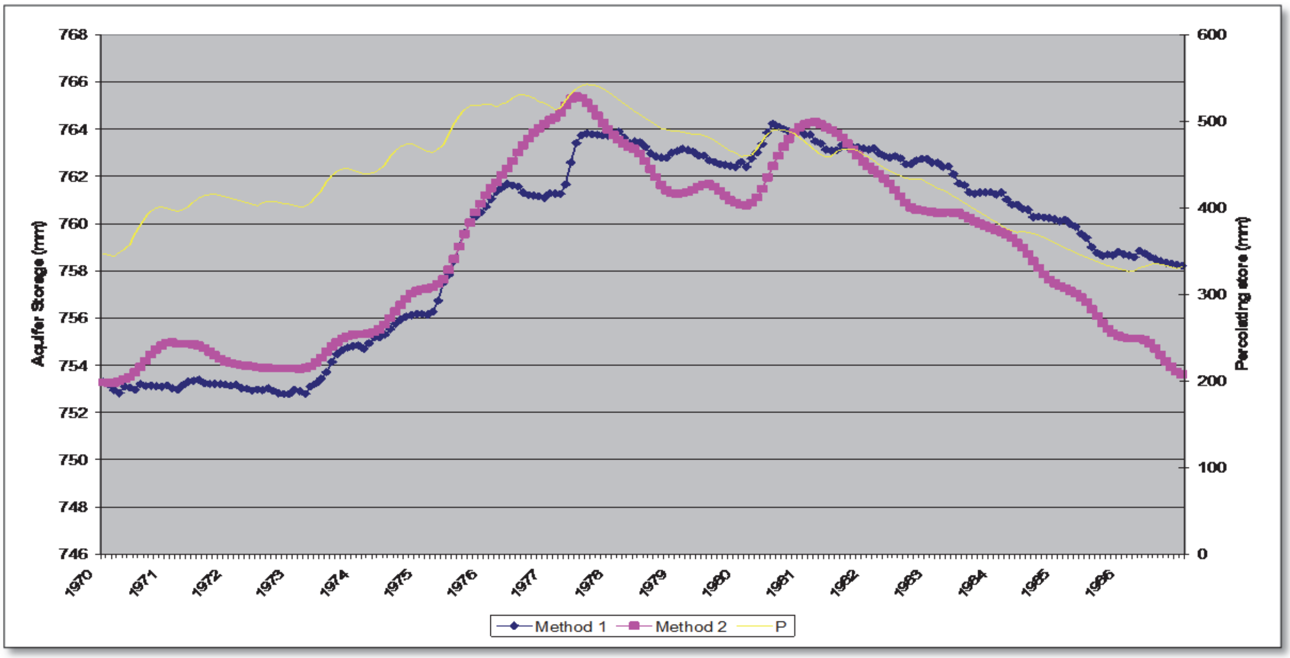


Figure 8.6: Aquifer storage and percolating storage calculated using methods 1 and 2

8.3.6 Groundwater Storage Increments from Recharge – Method 2

Recharge from soil moisture RE is added to a percolating storage zone defined by a parameter PMAX (mm), where its transmission to the aquifer is attenuated by:

$$PERC = RE_x * (\frac{P}{PMAX})^{PPOW} * \frac{RE_x}{\overline{RE}} \quad \text{.....} (8.5)$$

Where:

PERC = variable of percolation from the percolating store to the aquifer storage
REx = variable of the moving average of recharge RE for x months (1-120 months)
P = variable of percolating storage
PPOW = parameter of the relationship between storage and percolation ....(<1)
PMAX = maximum capacity of percolating storage
$\overline{RE}$ = mean monthly recharge

PMAX can be calculated as the mean water strike depth times storativity. The appropriate length of the moving average of recharge to utilise is dependent on the rate at which the recharge pulse is transmitted to the aquifer and is dependent on the potential volume of storage in the percolating zone. It can be estimated by PMAX divided by the average annual recharge times 0.5. Increasing the length of the moving average attenuates recharge, reducing peak recharge volumes.

If incrementing the percolating store by RE causes storage P to rise above PMAX, the excess recharge (EXRECH) is dumped directly to the aquifer store. In each month P is incremented by recharge RE, and decremented by PERC and EXRECH, generating a time series of aquifer storage and percolating storage (Figure 8.6)

.

The addition of the percolating store is to lag recharge RE generated from the soil using a moving average of recharge and the level of storage relative to the maximum volume of the percolating zone. Using this approach, percolation PERC is similar to recharge RE generated by method 1 (Figure 8.7).

Aquifer storage STORE is incremented by PERC.

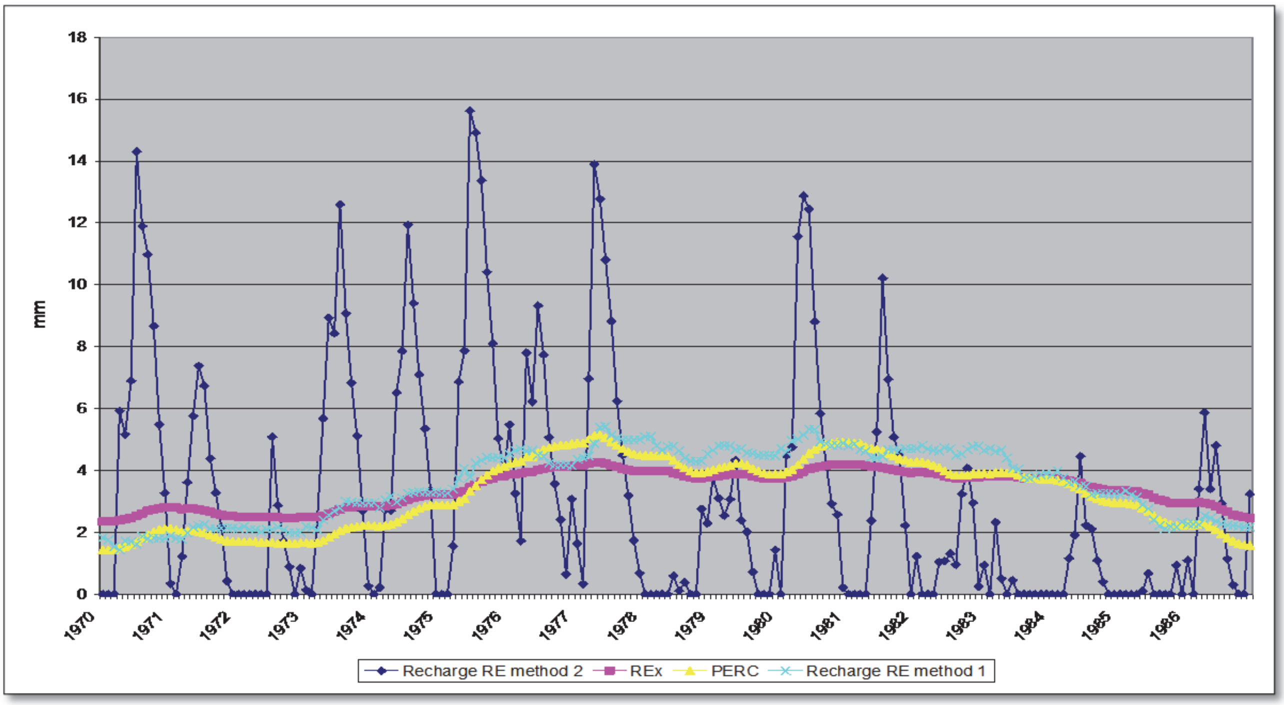


Figure 8.7: Recharge RE calculated by methods 1 and 2, the 132 month moving average of recharge Rex and the percolation to the aquifer PERC

8.3.7 Evapotranspiration from Shallow Groundwater – Methods 1 and 2

Where a shallow water table exists, and riverine vegetation or wetlands are thought to be sustained by groundwater, a routine to deplete groundwater storage is utilised.

Monthly rainfall is imported directly from WR90. Mean annual A-Pan evaporation, the percent monthly distribution of evaporation and the monthly Acocks Veld type crop factors from WR90 are also entered, as is the area over which evapotranspiration can take place. Monthly evapotranspiration is calculated by the product of mean annual evaporation, monthly distribution and crop factor. Rainfall is subtracted from evapotranspiration to obtain evapotranspiration demand from groundwater. When rainfall exceeds evapotranspiration demand evapotranspiration from groundwater is defaulted to 0, since it is assumed that the evapotranspiration demand will be met from soil moisture storage.

Evapotranspiration demand is multiplied by an aquifer storage factor to allow evaporation to decrease as groundwater storage is depleted. Evapotranspiration occurs at the maximum rate when groundwater storage is at aquifer capacity and declines towards 0 as groundwater storage drops to a level below the stream channel, defined by a parameter of static water level.

Evapotranspiration from groundwater is therefore calculated by:

$$((MAE * MDIST * CROP) - RAIN) * AREA * (STORE - SWL / CAP - SWL) \text{ ....} (8.6)$$

Where:

MAE = mean annual evaporation
MDIST = monthly distribution fraction of evaporation
CROP = monthly A pan crop factor for appropriate Acocks vegetation cover
RAIN = input data of monthly rainfall
AREA = riverine area where evapotranspiration from groundwater can take place
SWL = parameter of static water level

An error check is included to ensure evapotranspiration does not become negative if groundwater level drops below the static water level due to high levels of abstraction.

Evapotranspiration is subsequently decremented from groundwater storage.

CAP can be obtained from the Map of National Groundwater Resources Map of South Africa as the product of 'Recommended Drilling Depth Below Groundwater Level' and storativity. SWL is calculated as aquifer capacity less the degree of annual groundwater level fluctuation (in mm) times storativity. Hence the static water level can be expected to be 20-50 mm less than aquifer capacity, depending on the nature of the aquifer.

8.3.8 Groundwater Outflow – Methods 1 and 2

Groundwater is allowed to flow out of a catchment to simulate underflow and regional groundwater flow that does not emerge in surface water courses within the catchment.

Groundwater outflow is calculated using the Darcian approach of the product of parameters of transmissivity T and the hydraulic gradient HG oriented out of the catchment. The hydraulic gradient fluctuates as a function of aquifer storage. The maximum hydraulic gradient is defined by a parameter HGRAD. This gradient is the hydraulic gradient oriented out of the catchment. The maximum value for HGRAD can be taken as the channel gradient. The hydraulic gradient HG is decremented as the groundwater storage drops to the Static Water Level by:

$$HG = HGRAD * (STORE - SWL / CAP - SWL) \quad \text{......} (8.7)$$

Where:

HGRAD = parameter of maximum hydraulic gradient

This format allows groundwater outflow to occur at a decreasing rate as the water level drops, until outflow stops when the static water level is reached. Groundwater outflow is allowed to become negative to simulate drawing in of water from adjacent catchments under conditions of large scale abstraction.

Groundwater outflow is decremented from groundwater storage.

8.3.9 Groundwater Baseflow and Transmission losses – Methods 1 and 2

After evapotranspiration and groundwater outflow have been decremented from groundwater storage, groundwater baseflow is calculated. Groundwater baseflow is calculated as a function of the head difference between groundwater and surface water. Groundwater head in each month is calculated as the difference between STORE and SWL. Surface water head is calculated from the monthly runoff volume divided by catchment area. When groundwater head exceeds surface water head, as can occur during low flow months, groundwater baseflow is generated, simulating effluent conditions. These are decremented from groundwater storage. When surface water head exceeds groundwater head, as can occur during very wet months, temporary influent conditions arise and transmission losses to bank storage or to the aquifer are simulated. These are incremented to groundwater storage STORE.

This system allows head differences to vary month by month due to both groundwater storage and streamflow variations, thereby overcoming problems based on assuming unrealistic constant head conditions in the river, as employed by MODFLOW.

Groundwater baseflow (GWBaseflow) and transmission losses are calculated using a non-linear equation to account for the effects of hydraulic resistance:

$$GWBaseflow = (1 - e^{(HEAD \times BPOW)}) * BFMAX \quad \text{......} (8.8)$$

Where:

BFMAX = parameter of the maximum rate of groundwater baseflow
BPOW = relationship between head difference and baseflow
HEAD = STORE – SWAL – RUNOFF/CATCHMENT ......(8.9)
RUNOFF = Input of streamflow
CATCHMENT = Catchment area

The parameters BFMAX and SWL can be calibrated by verifying that groundwater baseflow approximately equals total streamflow during the driest period on record. Where no interactions occur, BFMAX is set to 0.

In Method 1, if calculated groundwater baseflow calculated by eq. 8.8 exceeds baseflow from the hydrograph separation, groundwater baseflow is defaulted to baseflow.

This equation allows large increases in baseflow or transmission losses for small head changes when the head difference between surface and groundwater is small, but causes baseflow and transmission losses to approach the maximum value of BFMAX as the head difference becomes larger (Figure 8.8). As the head difference increases, the exchange of water thereby increases at an increasingly smaller rate.

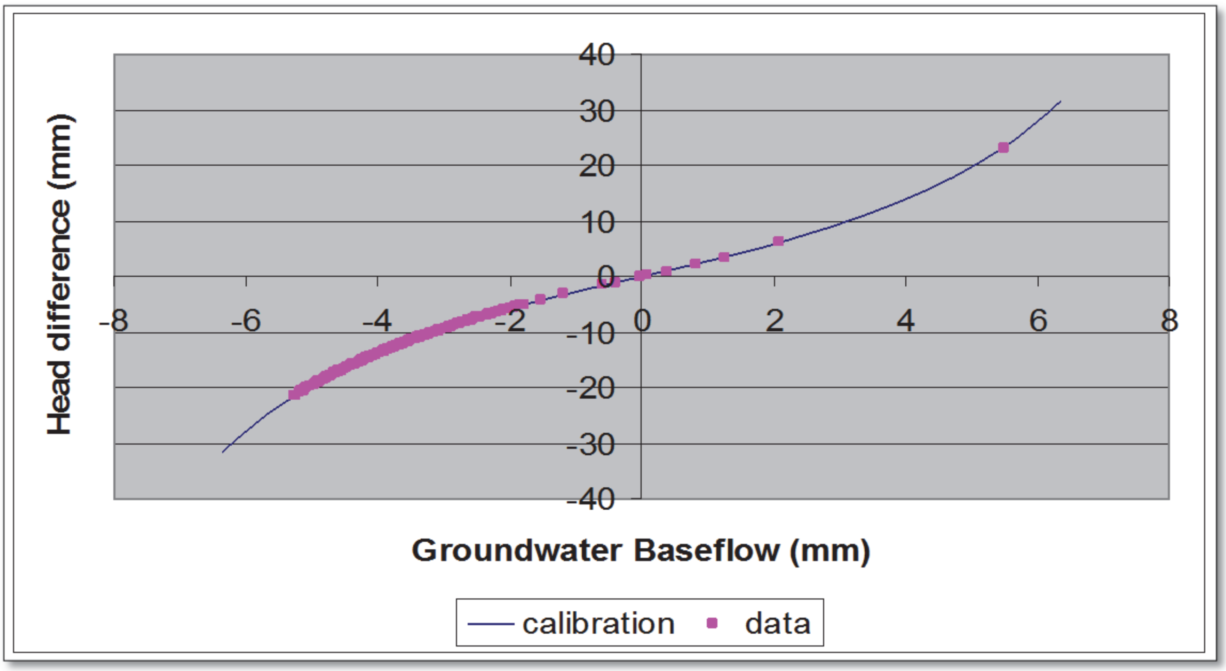


Figure 8.8: Relationship between groundwater baseflow (-ve) and difference in head (HEAD) between groundwater storage and surface water. +ve baseflow values imply influent conditions when transmission losses occur. Maximum baseflow has been set at 8 mm/month. CAP-SWL = 40 mm.

8.3.10 Interflow – Method 1

Under virgin conditions interflow is calculated as the difference between baseflow obtained from the hydrograph separation (Qg in eq. 8.2) and calculated groundwater baseflow (GWBaseflow in eq. 8.8):

$$\text{VIRGIN INTERFLOW} = \text{Qg} - \text{GWBaseflow} \qquad (8.10)$$

Since all potential recharge may not percolate into the aquifer when aquifer storage (STORE) is at capacity (CAP), it is assumed that the excess recharge contributes to interflow. This excess recharge is stored as a variable EXCESS1 by:

$$\text{EXCESS1} \qquad = \text{STORE} - \text{CAP if STORE>CAP}$$

This excess recharge can increase aquifer recharge if pumping depletes groundwater storage, allowing aquifer recharge to increase up to potential recharge during abstraction conditions. This increase in recharge would impact on interflow.
The depletion of interflow is calculated by:

$$\text{INTERFLOW} \qquad = \text{VIRGIN INTERFLOW} - \text{EXCESS1} + \text{EXCESS2} \ldots\ldots\ldots (8.11)$$

Where
EXCESS2 is recharge in excess of aquifer capacity under modified conditions:

$$\text{EXCESS2} \qquad = \text{STORE} - \text{CAP if STORE>CAP}$$

Note: Interflow has been lagged according to Pitman (GL)

8.3.11 Interflow – Method 2

Interflow is calculated as the sum of interflow from the soil moisture zone (4.3) and percolation PERC that would bring aquifer storage STORE above capacity CAP:

$$INTERFLOW = FT\left(\frac{S - SL}{ST - SL}\right)^{POW} + (STORE - CAP) \ldots\ldots\ldots \text{if STORE>CAP (8.12)}$$

Note: Interflow has been lagged according to Pitman (GL)

8.3.12 Groundwater Abstraction – Method 1 and 2

Groundwater abstraction can deplete both groundwater storage and groundwater baseflow in a non-linear fashion depending on the transmissivity and storativity of the aquifer, the distance from the stream channel and the time since pumping started and the volume of recharge in that month. The algorithms utilised are:

$$t' = \frac{4Tt}{x^2 S}$$

$$\%GW = \frac{GWMAX}{(1 + e^{(k3 + k2 \times t')})} \ldots\ldots\ldots (8.13)$$

Where

t’ = variable of dimensionless time
t = time since pumping started
T = Transmissivity parameter
S = Storativity parameter
X = distance from river parameter

%GW = variable of % of abstraction originating from groundwater storage in each month, with the remainder being groundwater baseflow depletion

GWMax = Maximum % of abstraction that can be taken from groundwater storage

k3 and k2 = calibrated curve fitting parameters with k2=-3 to -8 and k3 calibrated so that at early times 100% of abstraction is from groundwater.

The impact of such an algorithm is shown in Figure 8.9 for a borehole at various distances from the river. Over time, progressively more baseflow depletion occurs, however, this transition is distance dependent.

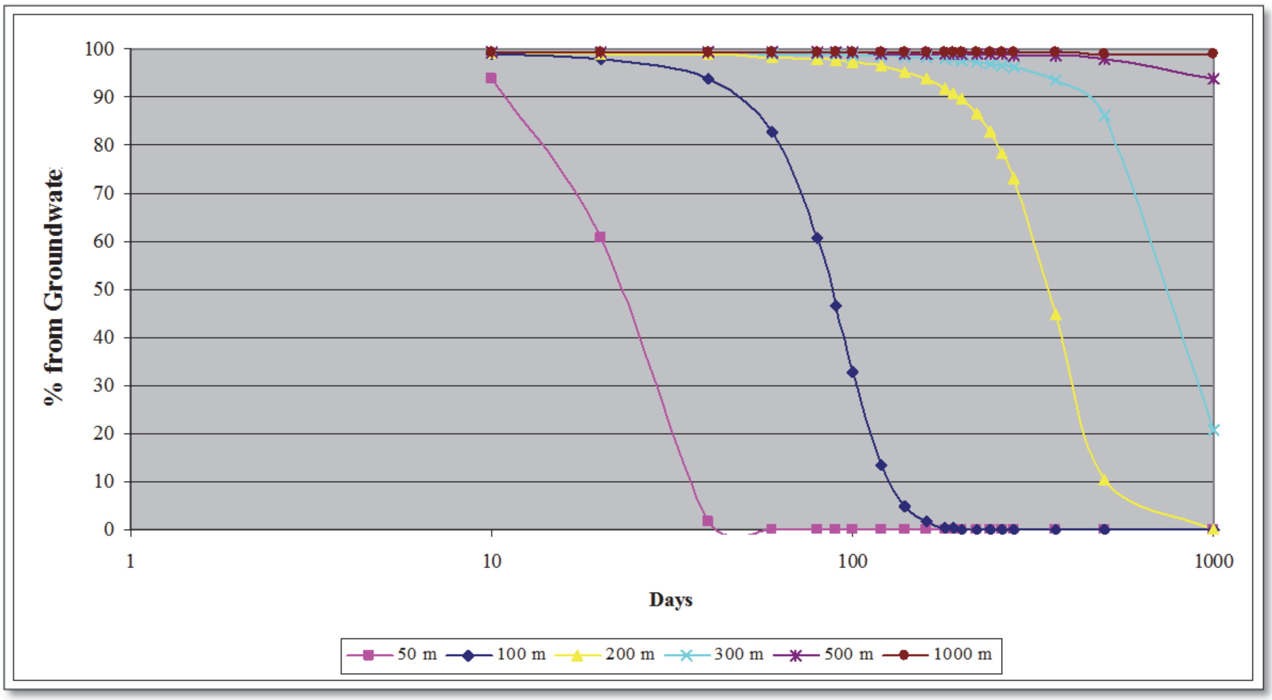


Figure 8.9: Impact of groundwater abstraction on baseflow depletion at various distances from the channel

To take into account recharge that replenishes storage, thereby allowing proportionally more water to be taken from groundwater storage, the parameter for time t in eq. 8.13 is modified by recharge, thereby allowing recharge to modify the impact on storage. This is achieved by:

$$\text{If } \frac{\text{Recharge or PERG}}{\text{mean monthly recharge}} < 1$$

Then,

$$t = (1 - \frac{Recharge\ or\ PERC}{mean\ monthly\ recharge}) * 30 + t_{i-1} \quad \text{...(8.14)}$$

$$if \ \frac{Recharge_i}{mean\ monthly\ recharge} > 1, t\ 13$$

Then,

$$t = t_{i-1} - \left(\frac{Rechargei}{mean\ monthly\ recharge} - 1 \right) * 30 \qquad \text{………………………………………………….}(8.15)$$

This algorithm allows an increased proportion of abstraction to be taken from groundwater store following recharge events exceeding the mean monthly recharge, and allows the transition to groundwater baseflow depletion to slow down during drier periods depending on the recharge volume.
The depletion of groundwater baseflow (Depletion) is calculated by:

$$Depletion = \frac{100 - \%\,GW}{100} * Abstractions * \frac{Recharge_i\ or\ PERC_i}{mean\ monthly\ recharge} \qquad \text{……………………}(8.16)$$

The correction of Depletion by the ratio of recharge to mean monthly recharge allows the portion of recharge above the mean monthly value to replenish the accumulated aquifer storage deficit. This accounts for the fact that groundwater baseflow does not become evident following recharge events after prolonged abstraction due for the need to rewater the aquifer to some extent before baseflow can occur.

The balance of abstraction volumes (abstraction-depletion) is taken from STORE. Depletion is subtracted from calculated groundwater baseflow (GWBaseflow), thereby depleting baseflow. If calculated baseflow depletion exceeds GWBaseflow, the excess is removed from groundwater storage (STORE). The volume taken from STORE would also cause increased transmission losses, due to a reduced groundwater HEAD.

8.4 Data Input

8.4.1 Parameters

The parameters required and comments on the source of data are shown in Table 8.2.

Table 8.1: Molde components. Parameters used only in method 1 are underlined. Parameters used on in method 2 are in Italics.

[1] P = Parameter, I = Initial condition, D = physical data, C = calculated, T = time series input data

Item	Status[1]	Source	Function	Comment	Common Range	Calibration
CATCHMENT CHARACTERISTICS						
Catchment Area (CATCHMENT)	D	WR90.	Volume and flux calculations	Default value set from internal lookup table		None
Aquifer thickness	P	National groundwater resources map, National Groundwater database, GRA II data an aquifer storage	Determines capacity of aquifer (CAP). Affects Evapotranspiration, groundwater baseflow, groundwater outflow and the generation of interflow as excess recharge	Based on difference between SWL and water strikes in an aquifer. Can be regionalised by geological domain. Must be multiplied by borehole success rates in catchments where groundwater occurrence is limited	10-50	Generally none. Increasing this value generally makes groundwater baseflow less responsive to recharge
Storativity (S)	P	National groundwater resources map, National Groundwater database, GRA II data an aquifer storage	Determines capacity of aquifer. Impacts on transition from aquifer storage to baseflow depletion during abstraction	Can be regionalised by geological domain	0.001-0.2	Increasing this value generally makes groundwater baseflow less responsive to recharge. It also results in a longer time delay before abstraction impacts on baseflow
Aquifer Capacity (CAP)	C	Calculated internally from Storativity and aquifer thickness			Depends on aquifer thickness and storativity	
Initial groundwater store	I	Calibration	Initial storage level of aquifer	Calibrated so that long simulation under virgin conditions results in little change in storage. If not calibrated impact on final results is minimal since change in storage over long time period has little impact on mean annual values	Between SWL and CAP	Usually set half way between static water level and aquifer capacity. Calibrated so that Aquifer Storage Change in the Virgin water balance is approximately zero, indicating no change in storage over the long term
MAP (RAIN)	D	WR90	Controls evapotranspiration	Used to calculate monthly rainfall from WR90 monthly rainfall distribution files		None
Static water level (SWL)	P	Calibrated regionally. Generally set to CAP – storativity x annual groundwater level fluctuation	Controls aquifer storage level at which groundwater baseflow, evaporation and groundwater outflow terminate	Can be regionalised by geological domain. Must be less than CAP. It is generally more than 50% of CAP in shallow or weathered aquifers and higher in deep seated fractured aquifers with little baseflow	30-80% of CAP	Increasing causes aquifer to remain full and groundwater baseflow to terminate as aquifer dewaters. Reducing results in more, less responsive and more persistent groundwater baseflow
Unsat Store (PMAX)	P	Calculated from median depth to water strike times storativity	Controls rate at which recharge percolates to aquifer	Used to lag the time between recharge and the groundwater baseflow response	10-400	Increasing causes recharge to be more attenuated and groundwater baseflow to be less responsive
Initial Store	I	Calibration	Initial storage level of unsaturated percolating storage	Calibrated so that long simulation under virgin conditions results in little change in unsaturated percolating storage. If not calibrated impact on final results is minimal since change in storage over long time period has little impact on mean annual values	Between 0-PMAX	Usually set at about half of PMAX. Calibrated so that Storage Change is approximately zero, indicating no change in storage over the long term
Moving average of recharge (Rex)	P	Calculated from PMAX divided by mean monthly recharge times 0.5 to account for residual saturation. Recharge values are available from GRA II	Controls rate at which recharge percolates to aquifer	Used to lag the time between recharge and the groundwater baseflow response	1-132	Increasing causes recharge to be more attenuated and groundwater baseflow to be less responsive

Item	Status[1]	Source	Function	Comment	Common Range	Calibration
HYDROGRAPH SEPARATION						
Decay	P	Calibrated regionally	Determines baseflow from hydrograph separation. Controls rate of baseflow recession on falling limb of hydrograph	Calibrated so that 'baseflow calculated is approximately equal to 'Mean annual baseflow'. The parameter is generally high (>0.9) in strongly baseflow controlled rivers and low (<0.3) in rivers with no baseflow or a very rapid short duration baseflow response	0.3-0.99	Calibrated by observing baseflow during driest period on record. Setting it too low causes too low a baseflow.
Growth	P	Calibrated regionally	Determines baseflow from hydrograph separation. Controls rate of baseflow response on rising limb	Calibrated so that 'baseflow calculated is approximately equal to 'Mean annual baseflow'. The parameter is generally low (<0.05) in catchments with little baseflow and high (0.1-0.2) in catchments with significant baseflow	0.05-0.2	Calibrated so that 'baseflow calculated is approximately equal to 'Mean annual baseflow'. Increasing cause baseflow to increase.
Initial baseflow	I	Calibrated	Starting condition	Has very little impact on results as it only affects baseflow generated in first month.	<10% of mean annual baseflow	Not calibrated
Mean annual baseflow	D	WSAM	Not used in model	Included only as an aid in calibration of baseflow volumes. Default value set from internal lookup table		
Baseflow calculated	C	Calculated internally	Not used in model	Included only as an aid in calibration of baseflow volumes. Calculated from model baseflow time series		If it varies significantly from mean annual baseflow then decay and growth can be calibrated in method 1, or recharge parameters in method 2.
PITMAN PARAMETERS						
FT	P	WR90	Controls determination of Pitman S hydrograph separation in Method 1. Controls rate of interflow from the soil zone in method 2.	Method 1: Generally obtained from regional WR90 data and not calibrated. In catchments with no baseflow WR90 sets this parameter to 0. In this model the parameter cannot be zero and must have low non-zero value in dry catchments Method 2: used to generate a portion of total baseflow hence must be less than the value used in the Pitman model	WR90 value or less	Not calibrated in method 1. Calibrated to less than WR90 value if groundwater baseflow is to be generated in method 2. Increasing cause interflow to increase and be more responsive
ST	P	WR90	Determines maximum soil moisture store	Generally obtained from regional WR90 data and not calibrated Has no impact on results unless soil moisture is frequently at capacity	WR90 value	Not calibrated
SL	P	WR90	Determines soil moisture level at which interflow and recharge stop, hence controls recharge and interflow volumes	Method 1: Generally obtained from regional WR90 data and not calibrated. Method 2: Used as a threshold for recharge and interflow from the soil zone and set to allow interflow to stop or have very low value during dry periods	WR90 value or higher	Not calibrated in method 1. In method 2 increasing cause interflow and recharge to be more persistent and increases volumes
POW	P	WR90	Determines relationship between soil moisture and baseflow	Generally obtained from regional WR90 data and not calibrated In catchments with no baseflow WR90 sets this parameter to 0. In this model the parameter cannot be zero and is set to 3 in dry catchments	WR90 value	Not calibrated
GW	P	Calibrated	Controls potential recharge	This parameter is generally set slightly higher than FT and calibrated to achieve a groundwater balance between recharge and outflow	>FT	Increasing increases potential recharge. Calibrated so that water and aquifer balanced of the virgin water balance are approximately 0.

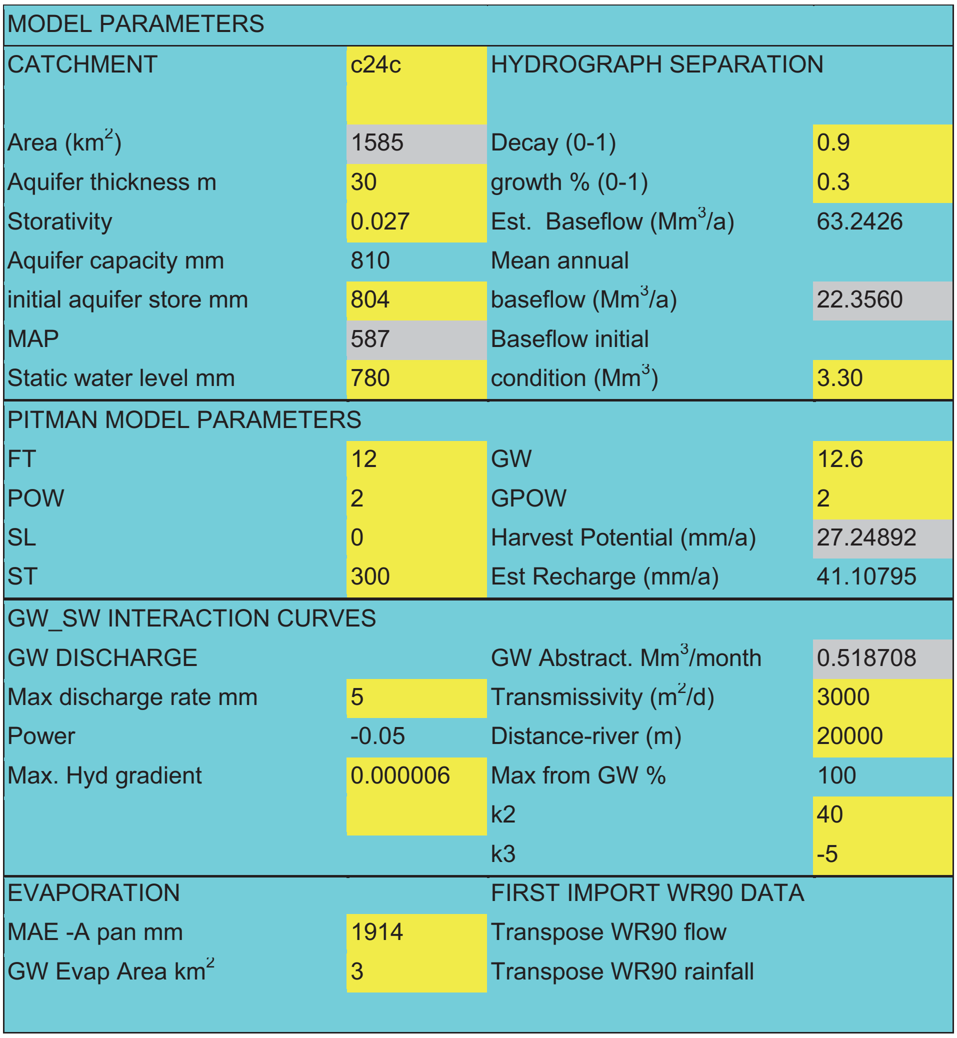
Item	Status[1]	Source	Function	Comment	Common Range	Calibration
GPOW	P	WR90	Affects potential recharge. Determines relationship between soil moisture and recharge	This parameter is set equal to POW, unless there is no baseflow, in which case it is set to 1 to allow recharge by indirect pathways in dry catchments. Used to control temporal distribution of recharge	1-3	Increasing reduces recharge with proportionally greater reductions at low soil moisture status.
Harvest Potential	D	WSAM	Not used in model	Included only as an aid in calibration of aquifer volumes. Default value set from internal lookup table		
Est. recharge	C	Calculated internally	Not used in model	Included only as an aid in calibration of potential and aquifer recharge volumes. Calculated from model potential recharge time series		If it varies significantly from Harvest Potential aquifer recharge may need to be calibrated using GW.
GROUNDWATER-SURFACE WATER INTERACTION						
Max groundwater discharge (BFMAX)	P	Calibrated regionally, or calculated from peak baseflow	Affects groundwater baseflow	Method 1: controls the distribution of baseflow between groundwater baseflow and interflow. It is set to zero where there is no baseflow, or baseflow only from springs. It is set low a low value (1 or 2 mm) in low permeability aquifers and to a high value (3-5 mm) in permeable aquifers Method 2: controls groundwater baseflow volumes and maximum baseflow	1-10	Increasing increases groundwater baseflow volume and peak rates
BPOW	P		Affects linearity of head difference-groundwater baseflow relationship	Can be used to control the duration at which groundwater baseflow occurs at the maximum rate BFMAX	-0.05	Generally not calibrated. If increased results in groundwater baseflow approaching BFMAX rate more slowly with increasing STORE.
GROUNDWATER EVAPOTRANSPIRATION AND OUTFLOW						
Hydraulic gradient (HGRAD)	D	Topographic maps or regionalised based on topography	Controls rate of underflow or groundwater outflow parallel to drainage	Generally set to the channel gradient or the hydraulic gradient oriented out of the catchment	0.00001-0.01	Increasing cause groundwater outflow to increase
MAE	D	WR90	Affects groundwater evaporation	Generally obtained from regional WR90 data and not calibrated		
GW evap. Area (AREA)	D	Regionally calibrated or measured from riverine vegetation area	Controls groundwater evapotranspiration	Area over which vegetation can abstract water from the regional aquifer. Generally set at 1.5% or less in dry catchments up to 5% in wet forested catchments	1.5-5% of catchment area	Generally not calibrated. Increasing causes groundwater evapotranspiration to increase and baseflow to decrease
Transmissivity	P	NGDB, best guess, test pumping data	Affects groundwater outflow and impact of abstraction	This parameter must be set to a regional median value, and not values obtained from test pumping of high yield boreholes	1-3000 but generally 2-10	Increasing this value increases groundwater outflow and results in a more rapid baseflow depletion response to abstraction
IMPACTS OF ABSTRACTION						
GW abstraction	D	WARMS	Not used in model	Included only as an aid in determining abstraction. Default value set from internal lookup table and based on groundwater use in WARMS		
Distance-river (X)	D	Based on weighted mean distance of abstraction points from main channel	Affects distribution of abstraction between groundwater baseflow and aquifer storage depletion			Not calibrated

Item	Status[1]	Source	Function	Comment	Common Range	Calibration
Max % from groundwater (GWMAX)	P		Controls distribution of abstraction between groundwater baseflow and aquifer storage depletion	Usually set to 100%	100	Not calibrated
K2	P	Regional calibration	Controls distribution of abstraction between groundwater baseflow and aquifer storage depletion	Controls duration over which abstraction removes water from groundwater storage	0.05-0.5	Increasing causes abstraction to deplete groundwater storage for a longer period before impacts on baseflow occur
K3	P	Regional calibration	Controls distribution of abstraction between groundwater baseflow and aquifer storage depletion	Controls shape of transition between groundwater storage and baseflow depletion	-3 to -10	Increasing causes more rapid transition to baseflow depletion and a lower % abstraction from groundwater storage
TIME SERIES DATA						
Discharge	D	WR90 or weir data	Method 1: driving input of model. Basis for hydrograph separation Method 2: used for calibration only			
Pitman S (S)	D	Pitman model	Driving input of model			
Rainfall (RAIN)	D	WR90	Affects evapotranspiration	Used only to determine rate of groundwater evapotranspiration		
% of MAE (MDIST)	D	WR90	Affects temporal distribution of evapotranspiration	% monthly distribution of MAE. Used to distribute MAE between months		
Crop factor (CROP)	D	WR90	Affects temporal distribution of evapotranspiration	Monthly distribution based on Acocks vegetation type. Affects efficiency of evapotranspiration relative to A-pan data.		
Abstraction	D		Affects baseflow depletion aquifer storage	Volume of groundwater abstraction		

8.4.2 Input Interface

8.4.2.1 Method 1

The parameter input screen is shown in Figure 8.10, with input parameters highlighted in yellow. Grey highlighted fields are internal data displayed by LOOKUP tables based on the Quaternary catchment, while blue fields are calculated from parameter values.



MODEL PARAMETERS			
CATCHMENT	c24c	HYDROGRAPH SEPARATION	
Area (km^2)	1585	Decay (0-1)	0.9
Aquifer thickness m	30	growth % (0-1)	0.3
Storativity	0.027	Est. Baseflow (Mm^3/a)	63.2426
Aquifer capacity mm	810	Mean annual	
initial aquifer store mm	804	baseflow (Mm^3/a)	22.3560
MAP	587	Baseflow initial	
Static water level mm	780	condition (Mm^3)	3.30
PITMAN MODEL PARAMETERS			
FT	12	GW	12.6
POW	2	GPOW	2
SL	0	Harvest Potential (mm/a)	27.24892
ST	300	Est Recharge (mm/a)	41.10795
GW_SW INTERACTION CURVES			
GW DISCHARGE		GW Abstract. Mm^3/month	0.518708
Max discharge rate mm	5	Transmissivity (m^2/d)	3000
Power	-0.05	Distance-river (m)	20000
Max. Hyd gradient	0.000006	Max from GW %	100
		k2	40
		k3	-5
EVAPORATION		FIRST IMPORT WR90 DATA	
MAE -A pan mm	1914	Transpose WR90 flow	
GW Evap Area km^2	3	Transpose WR90 rainfall	

Figure 8.10: Parameter input screen-Method 1

8.4.2.2 Method 2

The parameter input screen is shown in Figure 8.11, with input parameters highlighted in yellow. Grey highlighted fields are internal data displayed by LOOKUP tables based on the Quaternary catchment, while blue fields are calculated from parameter values.

MODEL PARAMETERS			
CATCHMENT	b82b		
Area (km^2)	406	Unsat Store	0.1
Aquifer thickness m	20	Initial store	0.1
Storativity	0.01		
Aquifer capacity mm	200	Mean annual	
initial aquifer store mm	180	baseflow (Mm^3/a)	5.7530
MAP	702	Baseflow calculated	5.6195342
Static water level mm	170		
PITMAN MODEL PARAMETERS			
FT	3	GW	4.6
POW	2	GPOW	1
SL	190	Harvest Potential (mm/a)	16
ST	800	Est Recharge (mm/a)	19.186303
GW_SW INTERACTION CURVES			
GW DISCHARGE		GW Abstract. Mm^3/month	0.0003667
Max discharge rate mm	1.3	Transmissivity (m^2/d)	10
Power	-0.05	Distance-river (m)	20
Max. Hyd gradient	0.0005	Max from GW %	105
		k2	0.1
		k3	-3
EVAPORATION		FIRST IMPORT WR90 DATA	
MAE -A pan mm	1645	Transpose WR90 flow	
GW Evap Area km^2	12	Transpose WR90 rainfall	

Figure 8.11: Parameter input screen-Method 2

8.4.3 Outputs

The spreadsheet model produces a monthly time series and mean annual values for the following variables (Figure 8.12):

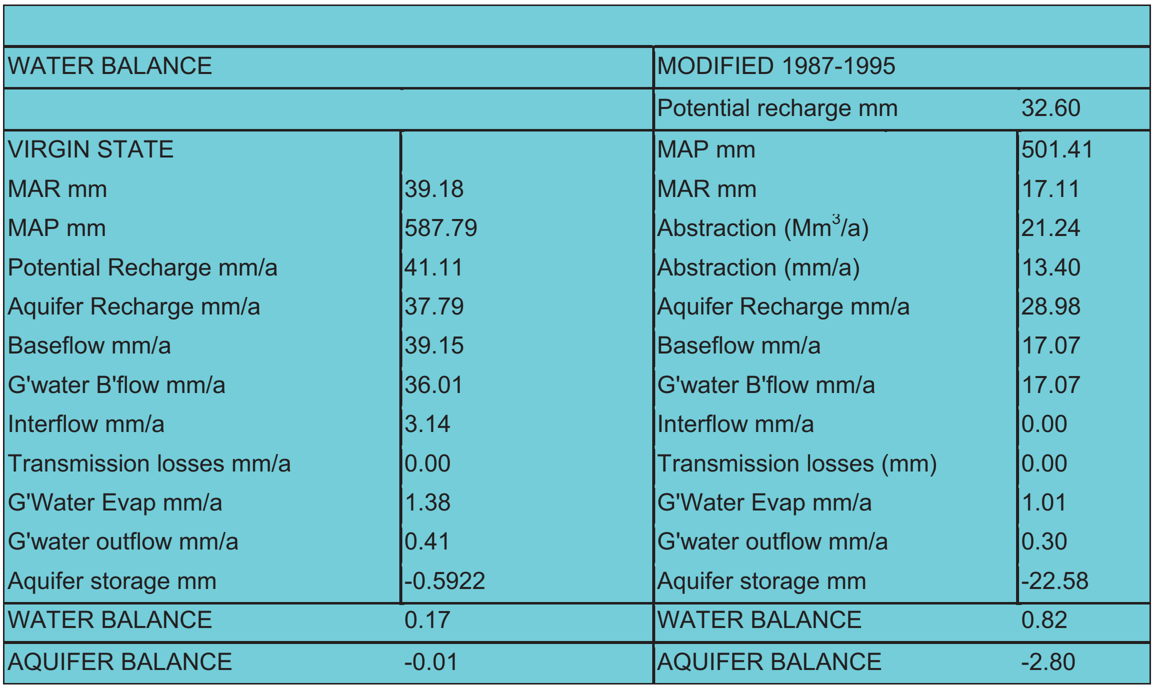
WATER BALANCE UNDER VIRGIN AND MODIFIED CONDITIONS

- Pitman S;
- potential recharge;
- aquifer recharge;
- baseflow;
- groundwater baseflow;
- interflow;
- transmission losses;
- groundwater evapotranspiration;
- groundwater outflow;
- groundwater storage;
- runoff and
- rainfall.

TIME SERIES GRAPHICS

In addition to time series graphics of the above monthly time series, graphs of the following value adding variables are included:

- duration curves of baseflow under modified and virgin conditions;
- duration curve of percentage baseflow depletion;
- annual rainfall versus recharge;
- probability curve of recharge non-exceedance and
- return period of drought recharge.



WATER BALANCE		MODIFIED 1987-1995	
		Potential recharge mm	32.60
VIRGIN STATE		MAP mm	501.41
MAR mm	39.18	MAR mm	17.11
MAP mm	587.79	Abstraction (Mm^3/a)	21.24
Potential Recharge mm/a	41.11	Abstraction (mm/a)	13.40
Aquifer Recharge mm/a	37.79	Aquifer Recharge mm/a	28.98
Baseflow mm/a	39.15	Baseflow mm/a	17.07
G'water B'flow mm/a	36.01	G'water B'flow mm/a	17.07
Interflow mm/a	3.14	Interflow mm/a	0.00
Transmission losses mm/a	0.00	Transmission losses (mm)	0.00
G'Water Evap mm/a	1.38	G'Water Evap mm/a	1.01
G'water outflow mm/a	0.41	G'water outflow mm/a	0.30
Aquifer storage mm	-0.5922	Aquifer storage mm	-22.58
WATER BALANCE	0.17	WATER BALANCE	0.82
AQUIFER BALANCE	-0.01	AQUIFER BALANCE	-2.80

Figure 8.12: Water balance display

8.5 Worked example – Middle Letaba B82B

8.5.1 Setup

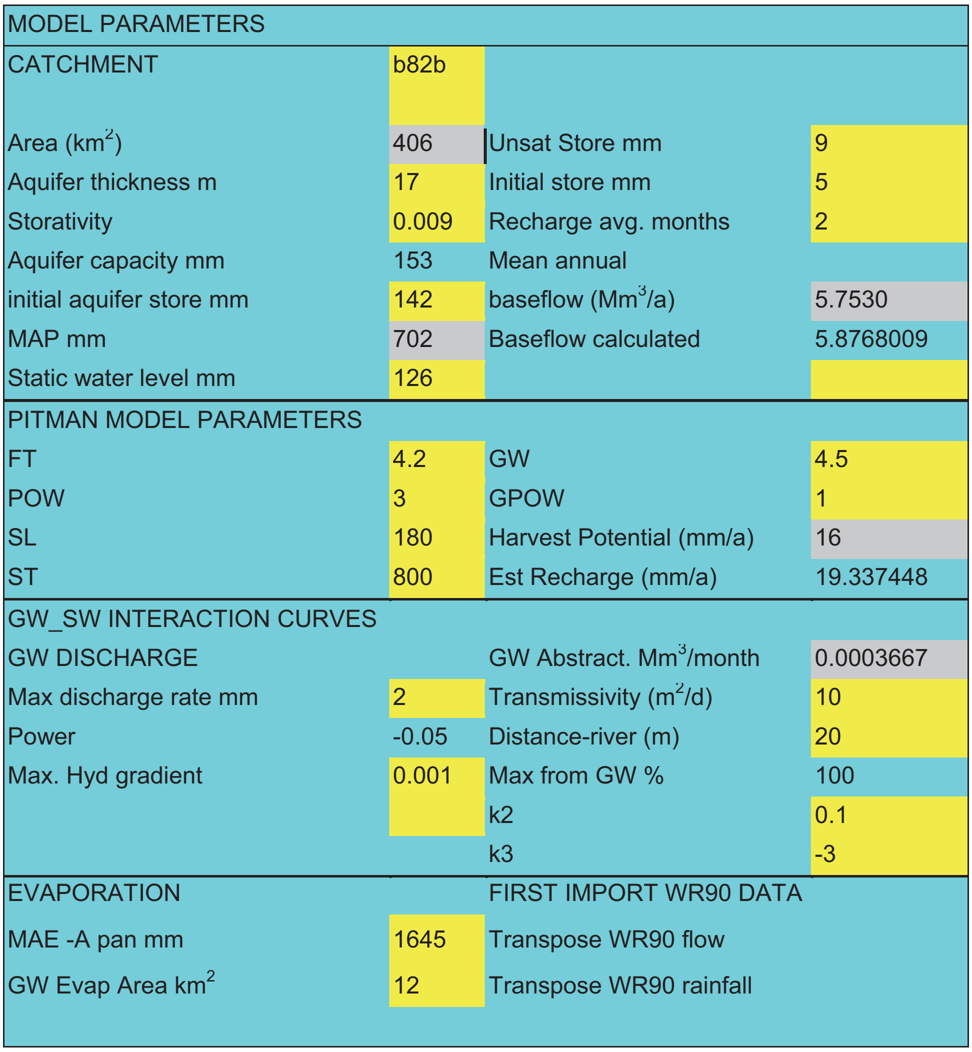
The spreadsheet model was applied to the middle Letaba catchment B82B and other catchments using method 2 in order to determine the impacts of groundwater abstraction on inflows into the Middle Letaba dam. The catchment is underlain by granites and is relatively steep. Baseflow is generated from high lying springs as interflow, and from groundwater in the valley bottoms.

The model was run for the period 1922-1996. Irrigation using groundwater began in 1986 and increased from 9.8 to 12.2 Mm^3/a. Irrigation was distributed into monthly abstraction volumes using crop water requirements. The MAR is 15.9 Mm^3/a.

The Pitman model parameters were used to generate the flow sequence and Pitman S values are shown in Table 8.2. Input parameters for the surface-groundwater model are shown in Figure 8.13.

Table 8.2: Parameters used for the Pitman model B82B

Parameter	Value	Parameter	Value
Rain Zone	B8A	ST	800
Zonevap	1B	FT	4.7
Ann.Evap	1550	zmin	45
Area	406	zmax	1100
eff_area	406	GW	0
MAP	702	PI	1.5
Afor	19	TL	0.15
POW	2	GL	0
SL	0	R	0.5



MODEL PARAMETERS			
CATCHMENT	b82b		
Area (km^2)	406	Unsat Store mm	9
Aquifer thickness m	17	Initial store mm	5
Storativity	0.009	Recharge avg. months	2
Aquifer capacity mm	153	Mean annual	
initial aquifer store mm	142	baseflow (Mm^3/a)	5.7530
MAP mm	702	Baseflow calculated	5.8768009
Static water level mm	126		
PITMAN MODEL PARAMETERS			
FT	4.2	GW	4.5
POW	3	GPOW	1
SL	180	Harvest Potential (mm/a)	16
ST	800	Est Recharge (mm/a)	19.337448
GW_SW INTERACTION CURVES			
GW DISCHARGE		GW Abstract. Mm^3/month	0.0003667
Max discharge rate mm	2	Transmissivity (m^2/d)	10
Power	-0.05	Distance-river (m)	20
Max. Hyd gradient	0.001	Max from GW %	100
		k2	0.1
		k3	-3
EVAPORATION		FIRST IMPORT WR90 DATA	
MAE -A pan mm	1645	Transpose WR90 flow	
GW Evap Area km^2	12	Transpose WR90 rainfall	

Figure 8.13: Input Parameters

8.5.2 Catchment Characteristics

The regional aquifer is considered to consist of a composite of weathered granites and alluvium. Data from GRA II indicate that the weathered zone aquifer has an average depth of 34 m and an average specific yield of 0.009. Given an area of 406 km^2, this would give a volume of 124 Mm^3 stored in the weathered zone. However, only 50% of boreholes are successful, indicating 50% of the area has very limited storage. As a result, aquifer storage was taken as 62 Mm^3. This is equivalent to a depth of 153 mm. Using this value for aquifer capacity, an average aquifer thickness depth of 17 m was calculated.

Water levels generally fluctuate about 3 m seasonally. When multiplied by the specific yield value of 0.009, this indicates that aquifer storage drops an average of 27 mm seasonally. Consequently a static water level of 126 mm was selected. (153 mm – 27 mm).

GRA II lists the catchment as having a storativity of 0.00017 for the fractured granite aquifer and 0.009 for the weathered aquifer. The average water level is 21 m deep. Approximately 3% of the catchment consists on valley bottom where a significant weathered zone exists. The remainder of the catchment consists largely of fractured granite. This gives a weighted mean storativity of 0.00043. When multiplied by the average depth to the water level, a volume of 9 mm can be calculated for the unsaturated percolating zone.

The length of the moving average of recharge was calculated from the unsaturated percolating store (9 mm), divided by the aquifer recharge listed in GRA II project 3B (22 mm/12 months) times 0.5. This gives a turnover time of 2.5 months. Consequently, a moving average of 2 months was selected. Project 3A lists recharge as 17 mm/a, which would yield a 3 month turnover time for the percolating storage.

To calculate groundwater evaporation, monthly rainfall distributions for rainfall zone B8A were imported from WR90 and transformed to monthly rainfalls based on an MAP of 702 mm. A-Pan data was converted from 1550 mm S-pan evaporation listed in WR90. Monthly distribution factors for zone 1B were applied. Crop factors applied were those for Inland Tropical Forest, as listed in WR90. An evaporation area of 12 km^2 was estimated based on 3% of the catchment area. This approximates the valley bottom area where groundwater is believed to be shallow.

Groundwater outflow was calculated based on a transmissivity of 10 m^2/d for the weathered zone. A maximum hydraulic gradient (HGRAD) of 0.001 was determined from channel gradients at the base of the catchment. This is the hydraulic gradient applied when groundwater storage is at aquifer capacity.

8.5.3 Baseflow Generation parameters

WSAM lists baseflow as being 5.75 Mm^3/a, or 14 mm/a, and the Harvest Potential as 16 mm/a. GRA II lists recharge as 17 mm/a (project 3A) or aquifer recharge as 22 mm/a and potential recharge as 24 mm/a.

To determine the maximum rate of groundwater baseflow, the hydrograph for the entire period was examined (Figure 8.14). It was assumed that at the end of the dry season (September), all discharge would be from groundwater. In the wettest period (1995), discharge was 0.8 Mm^3. This equates to a discharge rate of 1.97 mm, consequently a maximum discharge rate at aquifer capacity of 2 mm/month was selected.

Parameters FT, POW, GW and GPOW were calibrated to achieve a visual fit of the recession period of the hydrograph. Emphasis was placed on the period 1929-1939 to cover the driest period on record (Figure 8.15) and the period 1969-1996 to cover two wet periods and an intervening dry period (Figure 8.16).

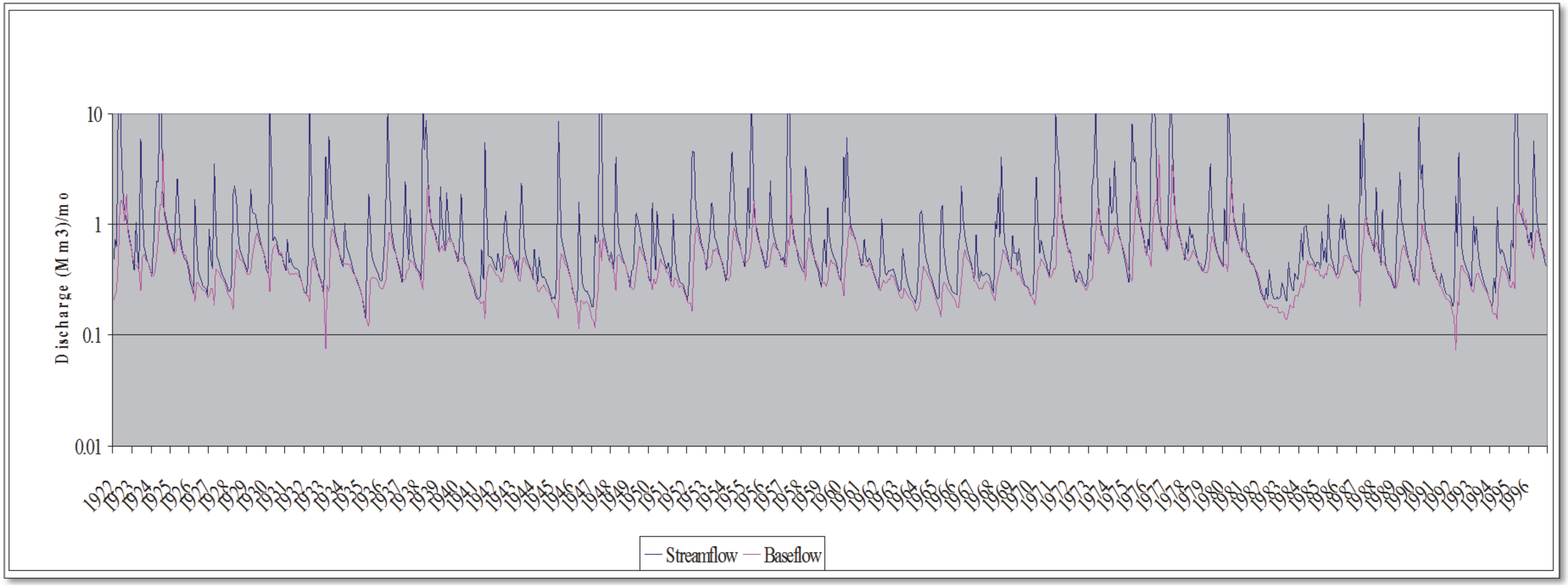


Figure 8.14: Discharge and calculated baseflow 1922-1996

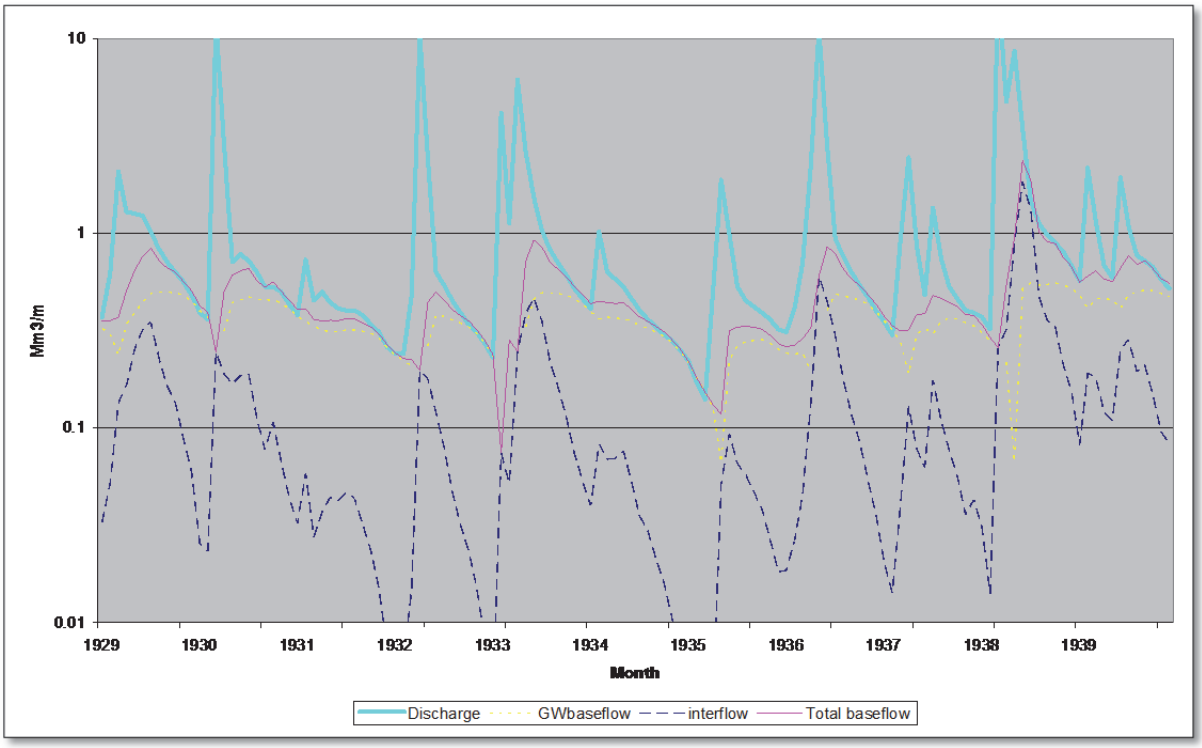


Figure 8.15: Discharge and calculated baseflow 1929-1939

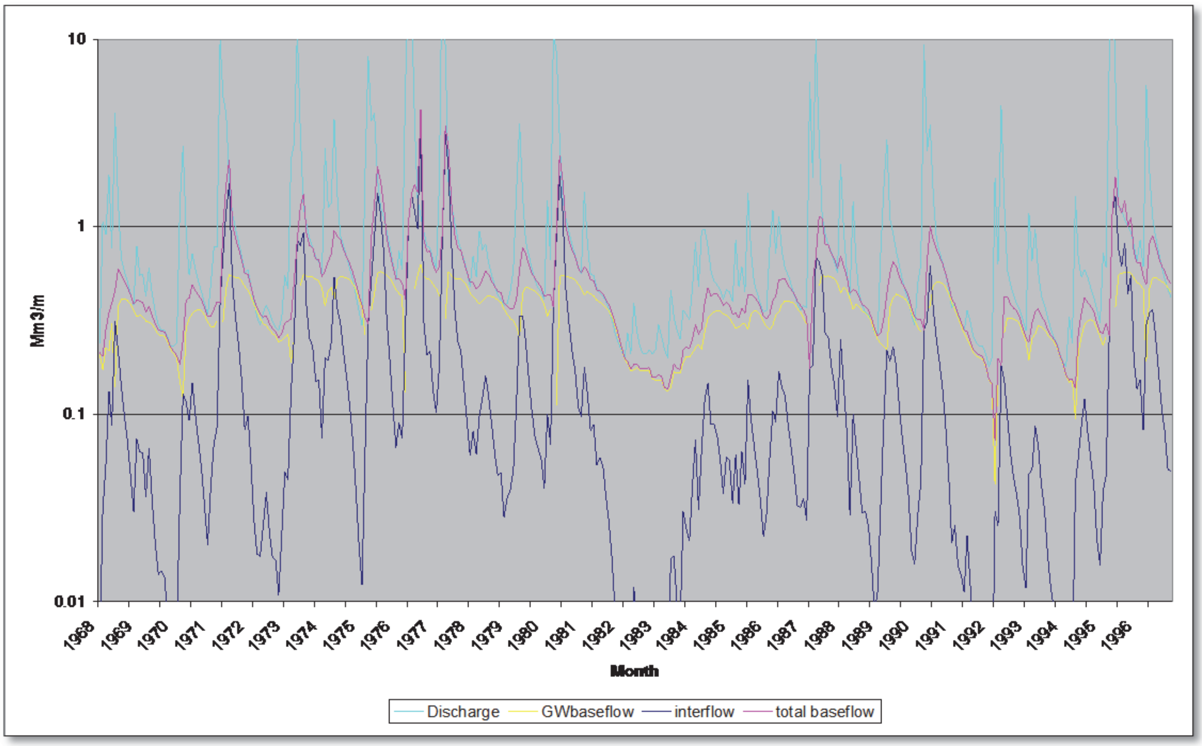


Figure 8.16: Discharge and calculated baseflow 1968-1996

8.5.4 Results

The resulting baseflow hydrograph is shown in Figure 8.12 and the water balance in Figure 8.17.

WATER BALANCE		MODIFIED 1986-1996	
		Potential recharge mm	23.61
VIRGIN STATE		MAP mm	705.70
MAR mm	39.25	MAR mm	23.42
MAP mm	701.97	Abstraction (Mm^3/a)	11.43
Potential Recharge mm/a	23.28	Abstraction (mm/a)	28.16
Aquifer Recharge mm/a	18.58	Aquifer Recharge mm/a	19.38
Baseflow	14.47	Baseflow mm/a	8.77
G'water B'flow mm/a	9.79	G'water B'flow mm/a	4.87
Interflow mm/a	4.69	Soil Interflow mm/a	4.23
Transmission losses mm/a	0.38	Transmission losses (mm)	8.54
G'Water Evap mm/a	8.67	G'Water Evap mm/a	0.40
G'water outflow mm/a	0.50	G'water outflow mm/a	-0.86
Aquifer storage change mm	-0.0148	Aquifer storage mm	-55.33
WATER BALANCE	0.01	WATER BALANCE	-4.33
AQUIFER BALANCE	0.00	AQUIFER BALANCE	-4.66

Figure 8.17: Simulated water balance

Calculated baseflow is 5.82 Mm^3/a, or 14.34 mm/a. Recharge is 23.3 mm/a, of which 18.7 mm/a enters the regional aquifer. These figures are similar to the values in WSAM and GRA II.

The relationship between annual rainfall and recharge is shown in Figure 8.18. The cumulative distribution of annual recharge, together with a probability distribution based on a presumed normal distribution is shown in Figure 8.19. There is a 10% probability of less than 11 mm of recharge. Return periods for recharge during drought periods is shown in Figure 8.18. A recharge of 11 mm/a corresponds to the 10-year drought.

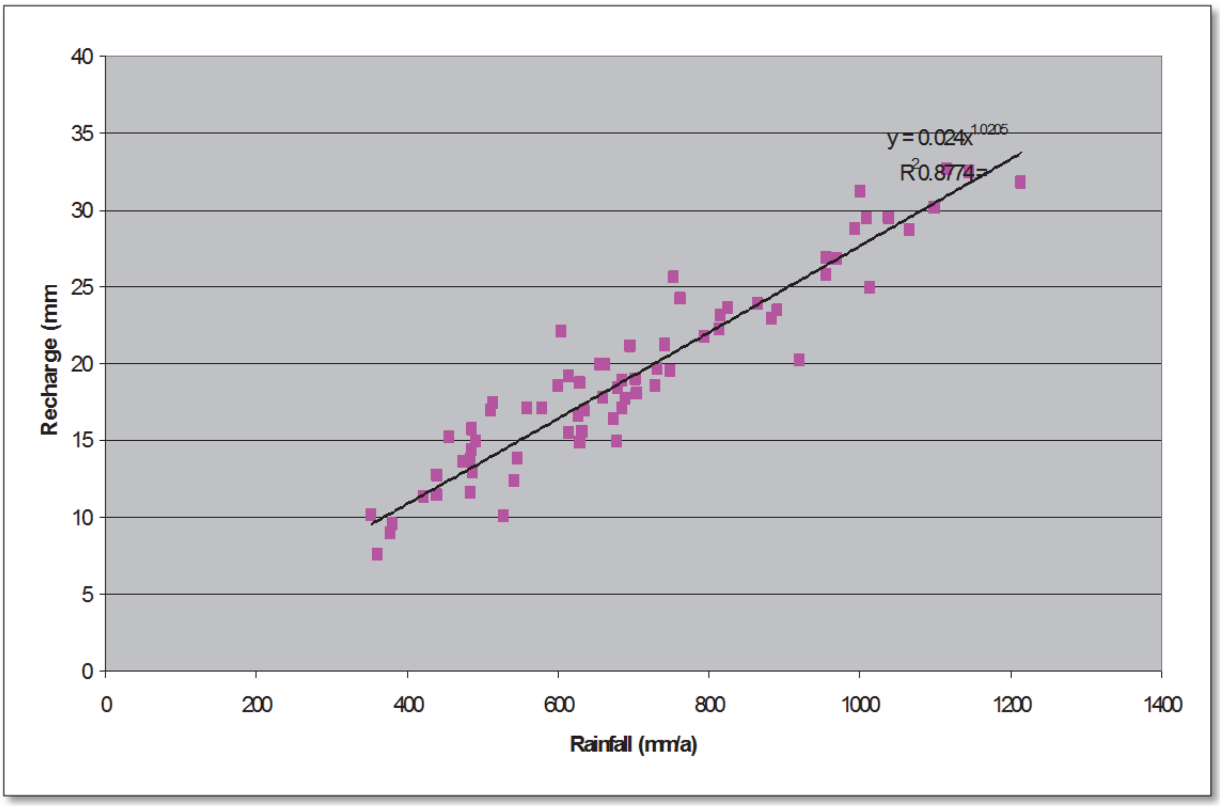


Figure 8.18: Relationship between annual rainfall and recharge

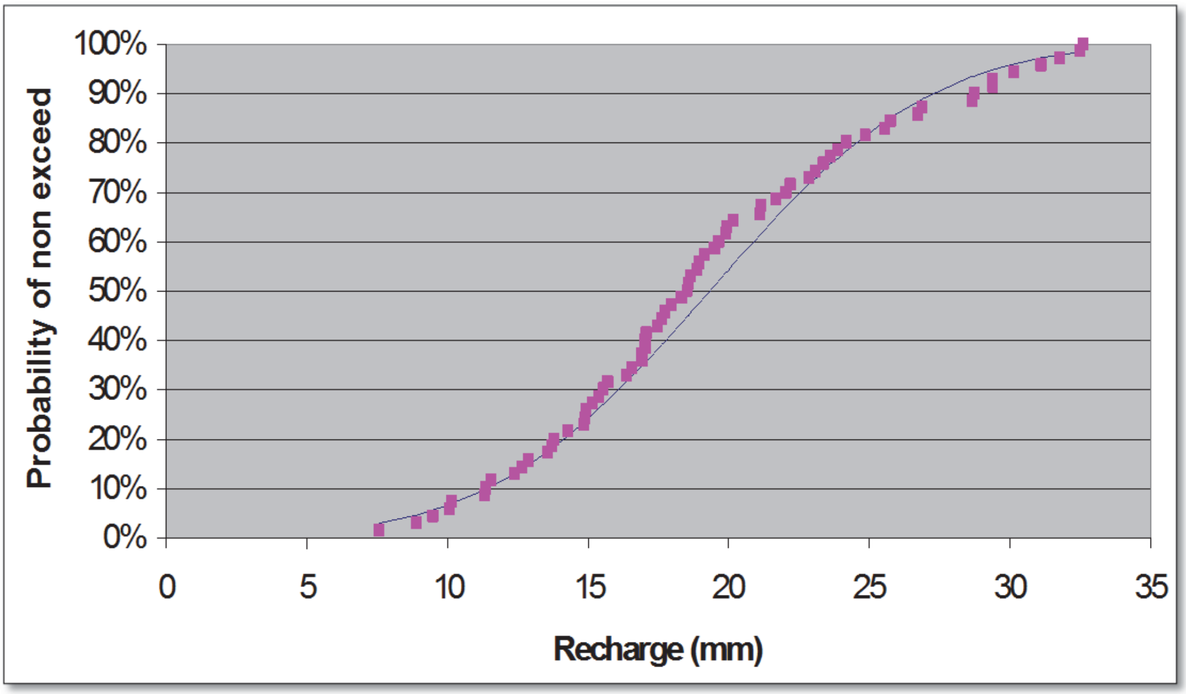


Figure 8.19: Probability distribution of annual recharge

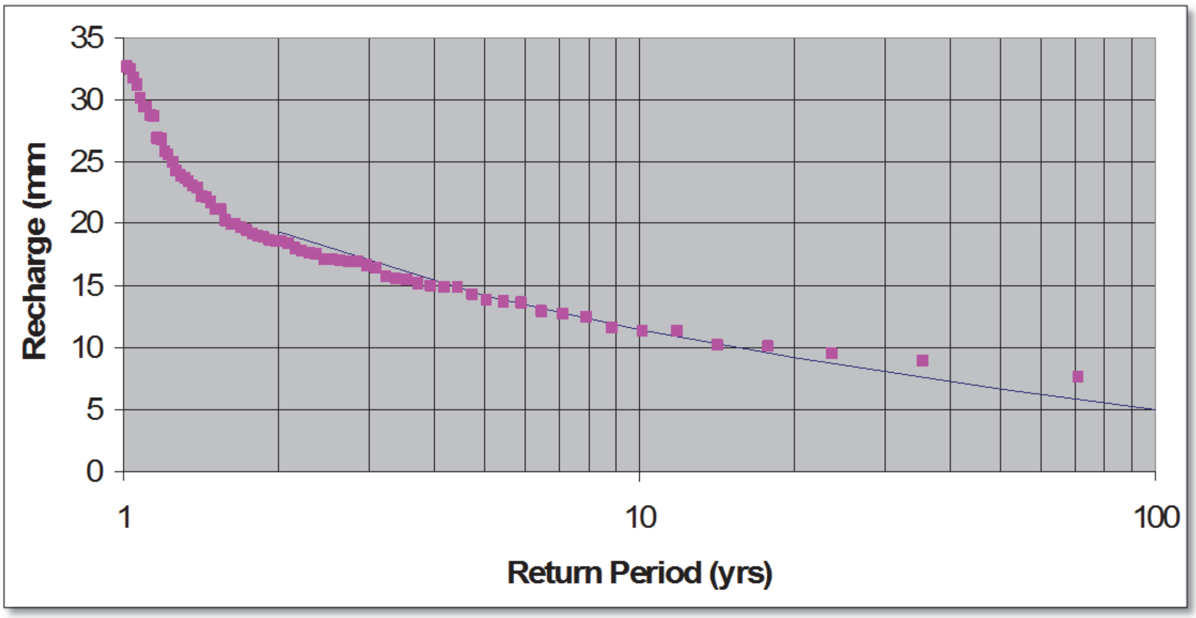


Figure 8.20: Return periods for drought recharge

8.5.5 Impacts of Abstraction

Groundwater abstraction in the catchment has grown from 24 mm/a to 30 mm/a in the period 1986-1996. This abstraction volume exceeds potential recharge.

The impacts of groundwater abstraction from boreholes at various distances from the channel are shown in Figure 8.21. Based on the location of abstraction boreholes in the alluvium in proximity to the river channel, a distance of 20 m was selected.

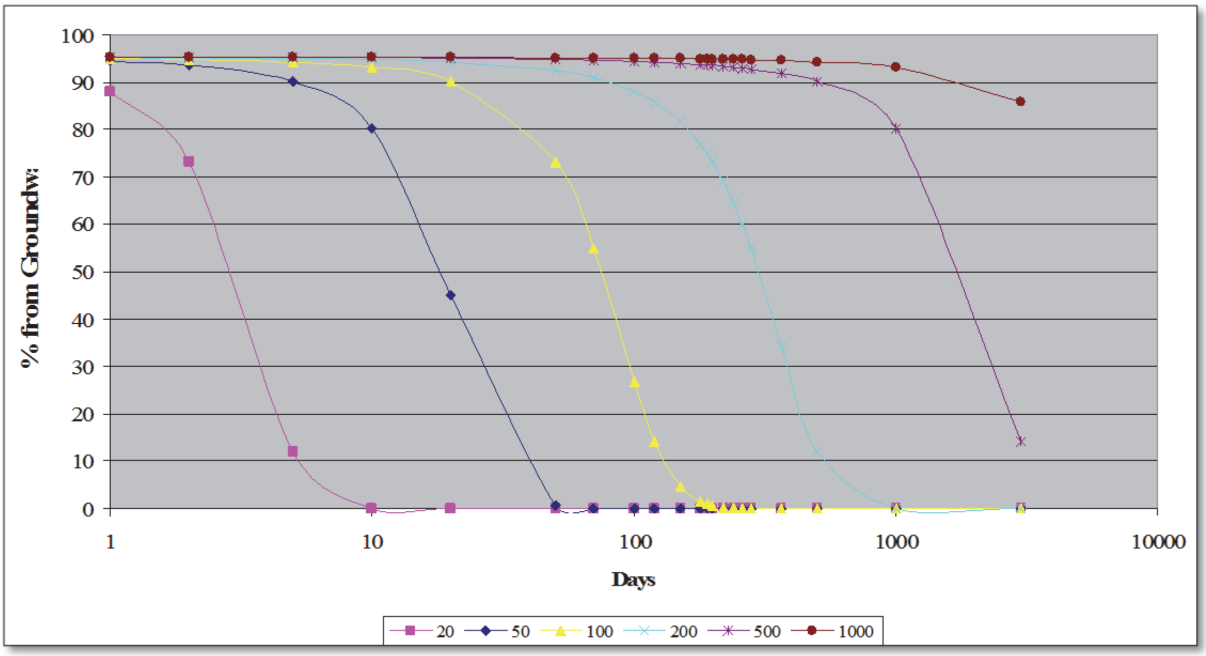


Figure 8.21: Impact of groundwater abstraction on baseflow depletion

Abstraction results in increased transmission losses (8.2 mm/a) and aquifer recharge (0.8 mm/a), a reduction in groundwater baseflow (5.7 mm/a) and evapotranspiration (8.3 mm/a), and the depletion of aquifer storage by 55 mm over the 11 year period (5 mm/a). Runoff is reduced by approximately 15.8 mm, or 40%.

The modified hydrograph is shown in Figure 8.22. The impact on the baseflow duration curve is shown in Figure 8.23. Baseflow is reduced by more than 90% for at least 15% of the time. Nearly zero baseflow conditions are encountered for more than 6% of the time. Increased transmission losses deplete runoff even further (Figure 8.22).

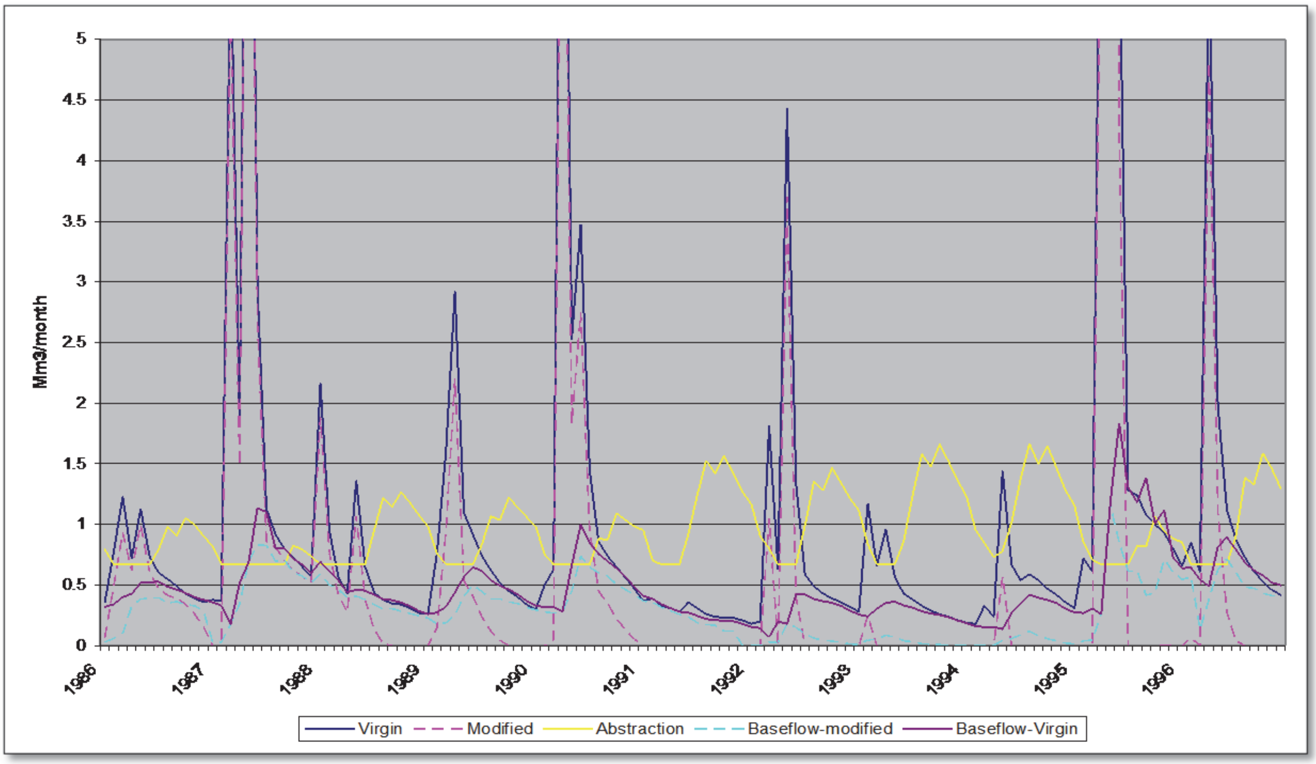


Figure 8.22: Hydrograph under virgin and modified conditions

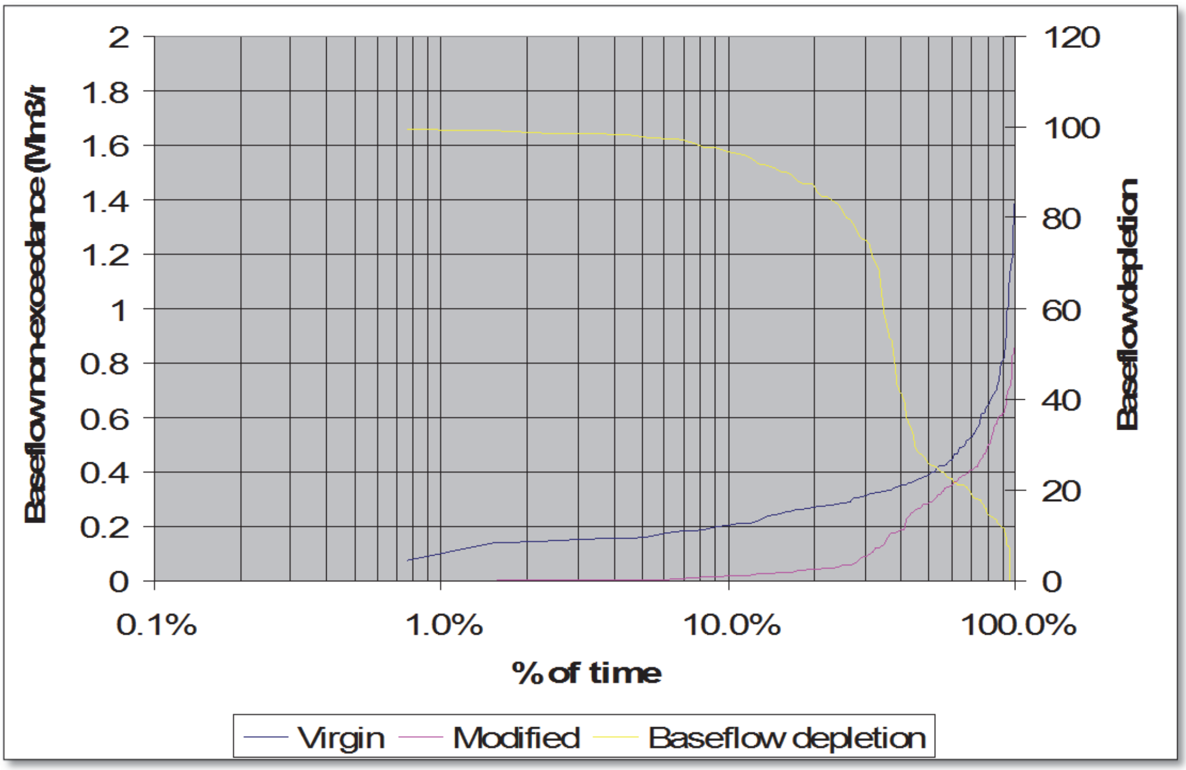


Figure 8.23 Baseflow duration curves for virgin and modified conditions

The impact on aquifer storage is shown in Figure 8.24. Abstraction results in aquifer storage declining by up to 50%, or 76 mm. This would result in a water level decline of 8.5 m.

The physical parameters described above were also used to simulate impacts on runoff in catchments B82A, B82C and B82D. Calculated total runoff volumes were verified against measured inflows at Middle Letaba Dam and were found to produce good results.

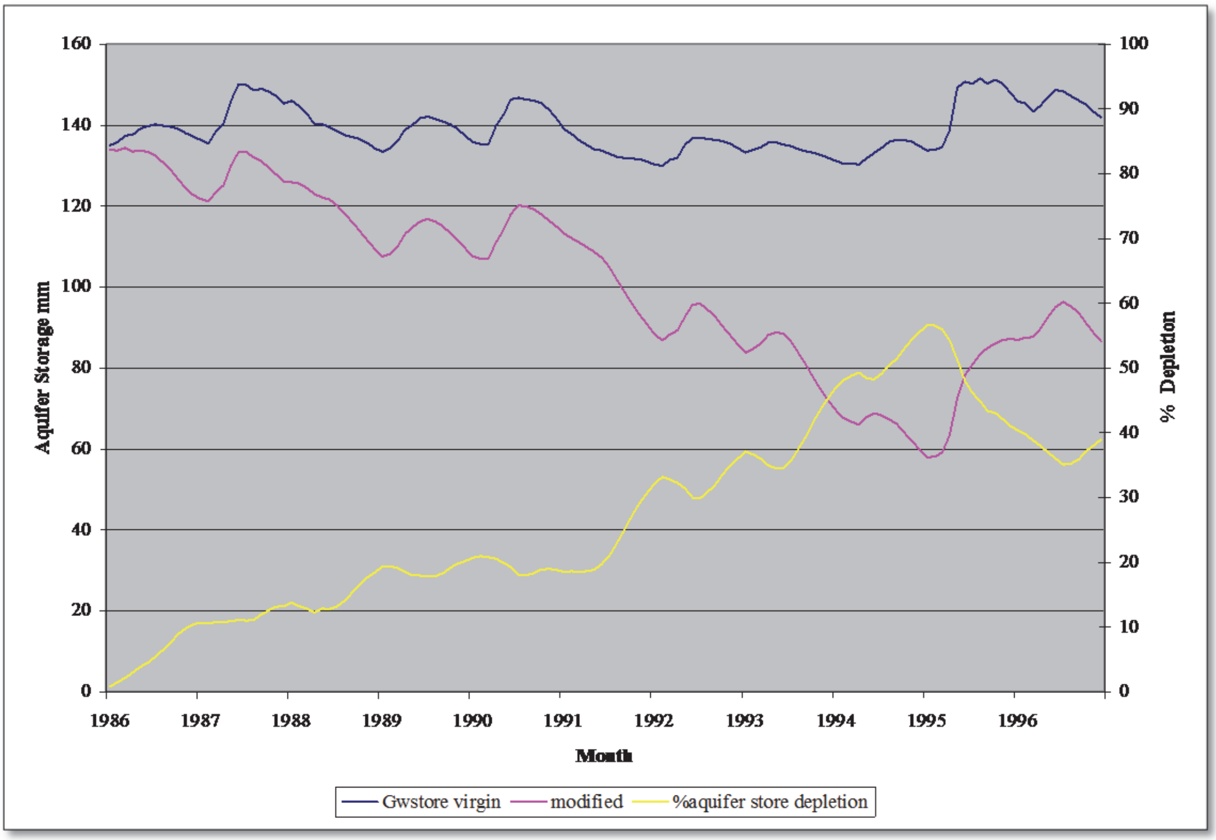


Figure 8.24: Groundwater storage under virgin and modified conditions

8.6 Conclusions

A methodology has been presented that can quantify recharge, groundwater baseflow, interflow, transmission losses, groundwater evapotranspiration and outflow and the impacts of groundwater abstraction on these processes at a monthly time scale.

The methodology is based on either hydrograph separations of monthly runoff data, or on Pitman S subsurface moisture storage data, to drive baseflow calculations. Parameters readily available from WR90 and WR2005, or physically quantifiable and readily regionalised are used, reducing the need to calibrate a large number of parameters.

The methodology has been incorporated into an MS-EXCEL spreadsheet with graphical facilities to simulate individual Quaternary catchments. Timer series data are calculated and displayed. The spreadsheet contains facilities for time series data analysis of baseflow duration, baseflow depletion, rainfall-recharge relationships, and drought recharge scenarios.

The methodology provides a rapid assessment of groundwater surface water interactions and the potential impacts of abstraction using basic data available primarily within WR90, with a minimum of intuitive parameters.

Current shortcomings with application of the methodology are as follows:

- uncertainty as to actual baseflow figures against which to calibrate calculated baseflow volumes;
- uncertainty and lack of recharge figures to calibrate GW and GPOW and
- arbitrary nature of K2 and k3 parameters controlling the relationship between abstraction and baseflow depletion due to lack of data regarding impacts of abstraction against which to calibrate these parameters.

Currently, no data is available to calibrate the algorithm of groundwater abstraction impacts on baseflow depletion. It is uncertain the degree to which distance from the borehole impacts on baseflow under transient conditions. For this reason, the parameters k2 and k3, which control the timing and rate of the transition between depletion of groundwater storage and baseflow depletion under fixed transmissivity and distance conditions, cannot be rigorously verified. If case studies based on long duration test pumping in the field could be obtained and calibrated, these parameters could possibly be fixed within the algorithm and removed, with only the catchment parameters of transmissivity and distance being used to control the impacts of abstraction.

8.7 References

ACT 108, 1997. Republic of South Africa Water Services Act.

Hughes, DA (2004). Incorporating groundwater recharge and discharge functions into an existing monthly rainfall-runoff model. Hyd. Sci J. (in press).

Sophocleous, Marios, 2002. Interactions between groundwater and Surface water: the state of the science. Hydrogeology J. 10:52-67.

Vegter, J.R., 1996. Recharge and streamflow. Workshop on groundwater-surface water issues in arid and semi-arid areas, Water Research Commission.

Vegter, J.R. (2001). Groundwater Development In South Africa. WRC Report No. TT134/00, Pretoria, South Africa.

8.8 Glossary

Table 8.3: Glossary

Term	Definition
Groundwater baseflow	Baseflow from the regional aquifer resulting from the water table being above river stage. This is water that could potentially be impacted upon by pumping from the aquifer
Harvest Potential	The maximum that can be abstracted per unit area based on recharge, transmissivity and aquifer storage constraints
Interflow	Baseflow from a combination of subsurface pathways, including baseflow from sources not in contact with the regional aquifer due to geological boundary conditions, baseflow from soil moisture, potential recharge that cannot percolate downwards due to saturated conditions (aquifer at capacity)
Potential recharge	Recharge that could reach the aquifer if the aquifer is not at capacity. This recharge includes recharge supplying baseflow for springs or perched aquifers, hence not all recharge is available to the regional aquifer
Aquifer recharge	Recharge reaching the regional aquifer and supplying groundwater baseflow, evapotranspiration, abstraction and outflow

9 SIMPLE WETLAND ALGORITHM (PRIOR TO WR2005 STUDY ENHANCEMENTS)

This algorithm permits the modelling of a wetland or aquifer with a minimum of parameters, which are:-

$\mathrm{CHC1}$ = wetland/aquifer volume (million cubic metres)
$\mathrm{CHC2}$ = wetland/aquifer area (km^2)
$\mathrm{CHC3}$ = wetland/aquifer recharge coefficient

Additional variables used in modelling the wetland/aquifer are as follows:-

Qr = flow in river to be adjusted for impact of wetland/aquifer
Qloss = reduction in riverflow
Enet = net evaporation loss (mm)
R = wetland/aquifer recharge (million cubic metres)
WETS = current value of wetland storage
SAE = computed wetland storage at month-end
SAVT = preliminary average wetland storage for the month
SAVA = final average wetland storage for the month
ETA = volume lost from wetland via evaporation

- Compute recharge and reduction in riverflow

$$\mathrm{R} = \mathrm{CHC3} \times (\, \mathrm{CHC1} - \mathrm{WETS} + \sqrt{}\mathrm{Qr}) \tag{9.1}$$

$$\mathrm{Qloss} = \mathrm{MIN}\,(\, \mathrm{R}\,,\, \mathrm{Qr}) \text{ i.e. recharge cannot be greater than riverflow} \tag{9.2}$$

- First assume wetland/aquifer storage capacity not exceeded

$$\mathrm{ETC} = 0.001 \times \mathrm{Enet} \times \mathrm{CHC2} \,/\, (\, 2 \times \mathrm{CHC1}) \tag{9.3}$$

$$\mathrm{SAE} = (\, \mathrm{Qloss} + \mathrm{WETS} \times (\, 1 - \mathrm{ETC}) \,/\, (\, 1 + \mathrm{ETC}) \tag{9.4}$$

$$\mathrm{SAVT} = (\, \mathrm{WETS} + \mathrm{SAE}) \,/\, 2 \tag{9.5}$$

- Check for exceedance of capacity (i.e. IF WETS > CHC1) and adjust

IF ($\mathrm{SAE} > \mathrm{CHC1}$) capacity is exceeded throughout month:

$$\mathrm{SAVA} = \mathrm{CHC1} \tag{9.6}$$

IF ($\mathrm{SAE} < \mathrm{CHC1}$) capacity is exceeded at start of month, then:

$$\mathrm{SAVA} = \mathrm{SAVT} - 0.5 \times (\, \mathrm{WETS} - \mathrm{CHC1})^2 \,/\, (\, \mathrm{WETS} - \mathrm{SAE}) \tag{9.7}$$

IF ($\mathrm{SAE} > \mathrm{CHC1}$ and $\mathrm{WETS} < \mathrm{CHC1}$) capacity is exceeded at end of month only:

$$\mathrm{SAVA} = \mathrm{SAVT} - 0.5 \times (\, \mathrm{SAE} - \mathrm{CHC1})^2 \,/\, (\, \mathrm{SAE} - \mathrm{WETS}) \tag{9.8}$$

If none of the above conditions apply, capacity is never exceeded:

$$\mathrm{SAVA} = \mathrm{SAVT}$$

- Adjust water balance for the month and reduce riverflow accordingly

$$\mathrm{ETA} = \mathrm{CHC2} \times \mathrm{Enet} \times 0.001 \times \mathrm{SAVA} / \mathrm{CHC1} \quad \text{....} (9.9)$$

$$\mathrm{WETS} = \mathrm{WETS} + \mathrm{QLOSS} - \mathrm{ETA} \quad \text{....} (9.10)$$

$$\mathrm{IF}\ (\mathrm{WETS} < 0) \quad \mathrm{ETA}{=}\mathrm{ETA} + \mathrm{WETS} \quad \text{....} (9.11)$$

$$\text{and } \mathrm{WETS} = 0 \text{....} (9.12)$$

$$\mathrm{Qr} = \mathrm{Qr} - \mathrm{Qloss} \quad \text{....} (9.13)$$

10 COMPREHENSIVE WETLAND SUB-MODEL INCLUDING OFF-CHANNEL STORAGE (WITH WR2005 STUDY ENHANCEMENTS) BY DR WV PITMAN

10.1 Description of Old Wetland Sub-model plus reasons for improvement

The old wetland model comprises an in-channel storage with a nominal storage volume and surface area, which can be exceeded during high flows. It works very much like a reservoir where downstream flow takes place only when the (nominal) storage capacity of the wetland is exceeded. This configuration is not realistic for wetlands comprising a defined channel that meanders through a wetland, feeding it with water only when the river channel capacity is exceeded. The flow of water between channel and wetland can be in the form of overbank spillage or via channels, or a combination of both. Examples of such wetlands are to be found in the Kafue River (Zambia) and the Pongolo River (RSA). The new wetland model described below is designed to simulate a wetland that is either off-channel or in-channel. It can also be employed to simulate the effect of a man-made off-channel storage dam for water supply.

10.2 Description of New Wetland Sub-model

The new wetland model is depicted in the diagram in Figure 10.1 below. (Showing a single link from river channel to wetland and another single link from wetland back into the channel facilitates visualization of the model. A real wetland has many links, where water can flow from channel to wetland and from wetland back into the channel, depending on water levels.) As is the case for the old model, the wetland has a nominal storage capacity and surface area, which can be exceeded. In the new model, however, the nominal values refer to the wetland storage (and associated area) below which there is no linkage to the river channel. Flow from wetland to channel is governed by the storage state of the wetland and is proportional to the storage volume over and above the nominal capacity. Flow from channel to wetland occurs when channel flow is above a prescribed threshold. The surplus flow is then apportioned between river channel and wetland link. If the model is to be used to simulate off-channel storage an upper limit can be set for the flow in the channel to wetland link, equivalent to the diversion capacity. The model also caters for local runoff entering directly into the wetland. This wetlands model links only to surface water flow and does not include groundwater fed wetlands.

A description of the various algorithms used to model the wetland follows. Units of million cubic metres (10^6 m^3) are used throughout for volumes and flow rates are in million cubic metres per month.

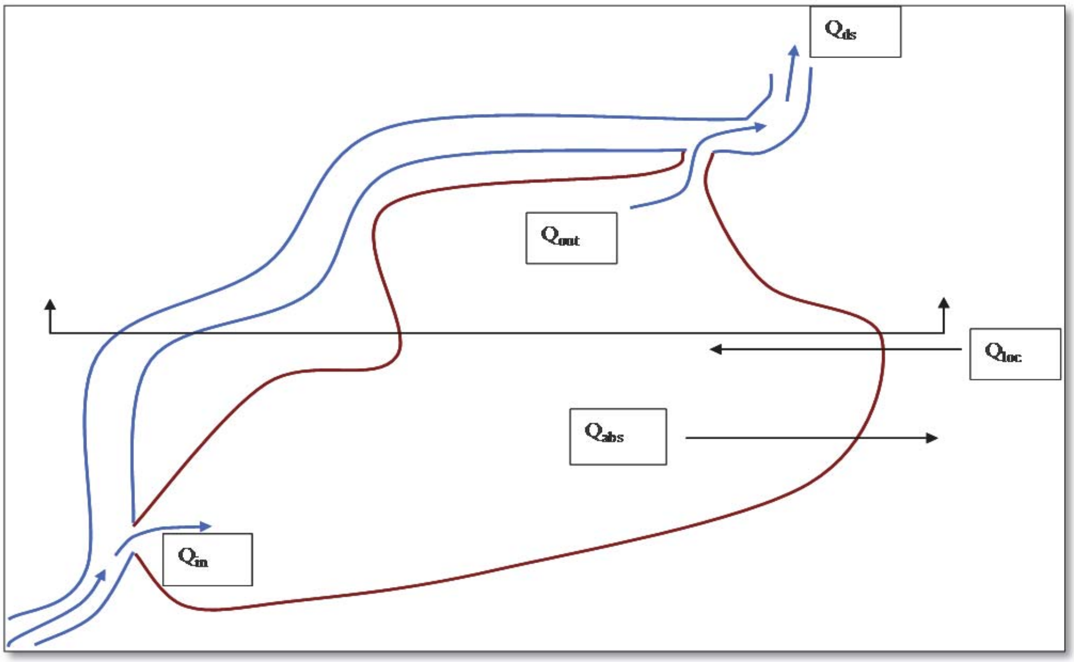


Figure 10.1: Schematic of a wetland

DESCRIPTION OF MAIN VARIABLES

Qloc = Local inflow directly into wetland
Qus = Flow in river channel upstream of wetland
Qds = Flow in river channel downstream of wetland
Qin = Flow into wetland form river channel
Qout = Flow into river channel from wetland
Qabs = Rate of abstraction from wetland/off-channel storage
Qevap = Rate of net evaporation loss from wetland
Qbf = Channel capacity above which spillage into wetland occurs
Qdiv = Diversion capacity into off-channel storage
Kin = Proportion of Qus above Qbf flowing into wetland
Kout = Proportion of wetland storage above Snom returned to channel
Snom = Nominal wetland storage volume
Anom = Nominal wetland surface area (km^2)
S1 = Wetland volume at start of month
S2 = Wetland volume at end of month
Save = Average wetland volume for month
Aave = Average wetland area for month (km^2)
a,b = Constants in wetland area-capacity eqn. $A=a\,S^b$
Enet = Net evaporation from wetland for month (m)

10.3 Water balance for wetland

$$\text{S2} = \text{S1} + \text{Qloc} + \text{Qin} - \text{Qout} - \text{Qevap} - \text{Qabs} \quad \ldots\ldots\ldots\ldots\ldots\ldots(10.1)$$

Inflow to the wetland is from the river channel, whereas outflow can be a combination of flow back into the channel, net evaporation loss and abstractions from the wetland (or off-channel storage). In times of heavy rain the net evaporation rate can be negative and constitute an additional input to the wetland.

10.4 Flow into wetland

$$\text{Qin} = \text{MIN}\,[\text{Qdiv}\,,\, \text{Kin} \times (\,\text{Qus} - \text{Qbf})] \quad \ldots\ldots\ldots\ldots\ldots\ldots(10.2)$$
$$[\text{or } 0 \text{ if } \text{Qus} < \text{Qbf}\,]$$

If flow in the channel is less than the threshold value Qbf, then there is no inflow. Above the threshold the inflow is a proportion of the channel flow above Qbf. If an off-channel scheme is being modelled, Qbf becomes the flow below which no diversion is allowed (say, for the Reserve) and Qdiv is the maximum rate of transfer to the off-channel dam, viz. the diversion capacity. For a natural wetland Qdiv is not used, hence an arbitrary large value is assigned in the model. An in-channel wetland can be modelled by setting Qbf equal to zero and Kin equal to 1, such that all flow enters the wetland.

10.5 Outflow from wetland

$$\text{Qout} = \text{Kout} \times (\text{Save} - \text{Snom}) \quad \ldots\ldots\ldots\ldots\ldots\ldots(10.3)$$
$$[\text{or } 0 \text{ if } \text{Save} < \text{Snom}\,]$$

Outflow from the wetland back into the channel occurs only when the wetland volume exceeds the nominal storage. The factor Kout determines the rate at which the surplus water drains back to the channel. For some very extensive wetlands a low value of Kout would be appropriate, signifying a slow release of water back to the channel. However, if an off-channel scheme is being modelled the value of Kout would be close to unity, since the dam would be provided with a spillway.

10.6 Evaporation from wetland

$$\text{Qevap} = \text{Enet} \times \text{Aave} \quad \ldots\ldots\ldots\ldots\ldots\ldots(10.4)$$

The net evaporation loss Enet is determined in the usual manner by subtracting rainfall from the gross evaporation, which is derived by applying a coefficient to the monthly pan evaporation. The relationship between wetland volume and surface area is given by the equation $A = aS^b$, where a and b are constants defined by the shape of the wetland basin. For most wetlands one has a good estimate of the nominal surface area (Anom) and the nominal volume (Snom) can be estimated by assuming an average water depth. The coefficient b can be derived by assuming a basin shape: a typical value for b is plus/minus 0.5. The value of a can then be determined by the following equation.

$a \quad = \text{Anom} / \text{Snomb}$ .. (10.5)

$= \text{Anom} / \text{Snom}0.5$……………………………………(if no estimate of b available)

The net evaporation can now be calculated from the wetland storage state as follows:

$\text{Qnet} \quad = \text{Enet} \times a \times \text{Save } 0.5 = \text{Enet} \times \text{Anom} \times (\text{Save}/\text{Snom})0.5$ ……(10.6)

10.7 Flow downstream of wetland

$\text{Qds} \quad = \text{Qus} - \text{Qin} + \text{Qout}$ ……………………………………………………………(10.7)

The flow downstream of the wetland is simply the upstream flow less inflow to the wetland plus outflow back to the river channel. For most months Qds will be less than Qus (i.e. Qin > Qout). However, periods immediately after high flow can be followed by a net increase in flow as floodwater drains back into the river channel.

10.7.1 Notes on Solution of Water Balance

Owing to the coarse time step (one month) it is necessary to perform some kind of iteration to achieve a water balance of sufficient accuracy. The model achieves this by making successive approximations to the average wetland storage (Save) until the difference between successive estimates is less than a predetermined value.

10.8 Preliminary Testing of New Wetland Model using the Kafue wetland

Hydrological modelling of the upper Kafue basin, which contains an extensive wetland, has been undertaken recently. It was during the course of this study that the shortcomings of existing wetland model (in WRSM/Pitman) were exposed, in that it was necessary to reduce dry season flows to zero in order to achieve the correct evaporative losses from the wetland. A stand-alone computer program (called SWAMP2) has been written for the purposes of development and testing. (Please note that variable names in the program are not necessarily the same as used in the preceding model description.)

10.8.1 Data inputs

The basic data required by the program is listed and described below.

Line1: 900 2500 2500 0.5 400 0.25 0.25
Line 2: 0.0 0.0
Line 3: 180 175 180 175 150 140 115 100 85 85 115 160
Line 4: 1969 1990
Line 5: 'kafue.ran'
Line 6: '4350.obs'
Line 7: ‘K2RQ58.ANS'

Line 1 contains the model parameters that need to be adjusted in the calibration process.

(The exception is the first variable, which can be obtained from rainfall information.) Some indication of the wetland area can usually be obtained from suitable mapping.

900	Mean annual precipitation on wetland (see description of Line 5)
2500	Nominal wetland surface area

Nominal wetland volume

Power coefficient of wetland area-volume equation

River channel capacity

Proportion of river flow (above capacity) flowing into wetland

Proportion of wetland volume (above nominal capacity) flowing back to river

Line 2 contains two variables for modelling an off-channel storage scheme, as follows:

Maximum diversion capacity (set to 0.0 if not applicable)

Rate of abstraction from wetland/off-channel storage

Line 3 contains the 12 mean monthly evaporations applicable to wetland (Oct to Sep)

Line 4 contains the first and last years of the period to be simulated

Line 5 contains the rainfall filename. Note that it is a file of monthly rainfalls as percentages of MAP, which gets converted to mm in the program.

Line 6 contains the file of monthly river flow upstream of the wetland.

Line 7 contains the file of local monthly flows that flow directly into the wetland. If there are no such flows then a blank filename (‘ ‘) is entered.

10.8.2 Model results

The model was calibrated on the flow record at a gauge downstream of the wetland. No attempt was made to “fine tune” the calibration – the main purpose of the exercise was to ascertain whether the model could simulate adequately the effect of the wetland on flows downstream of it.

The diagram on the top of the following page contains observed mean monthly flows upstream and downstream of the wetland, as well as the simulated downstream values. It shows how the model has reproduced the truncation of the high flows whilst leaving the low flows virtually unaffected.

The lower diagram is a plot of annual total flow volumes for the same three time series. What is evident from this diagram is that a regime change has taken place about 1981. Before this date the (observed) flows downstream are less than the upstream flows, whereas, after this date, the downstream flows are generally higher.

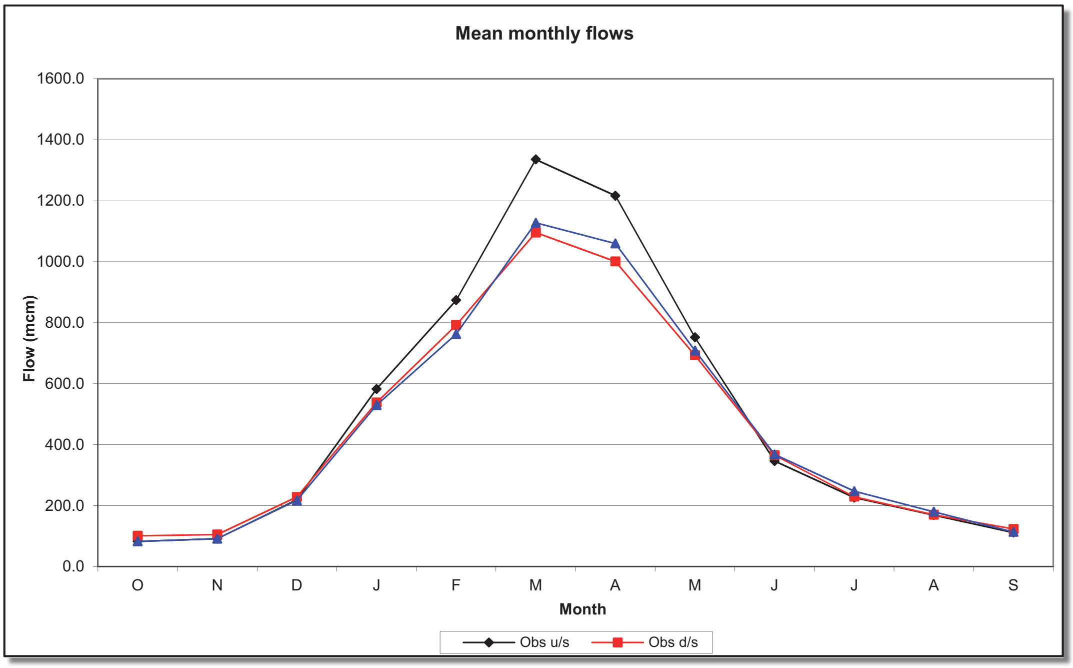


Figure 10.2: Mean Monthly Flows

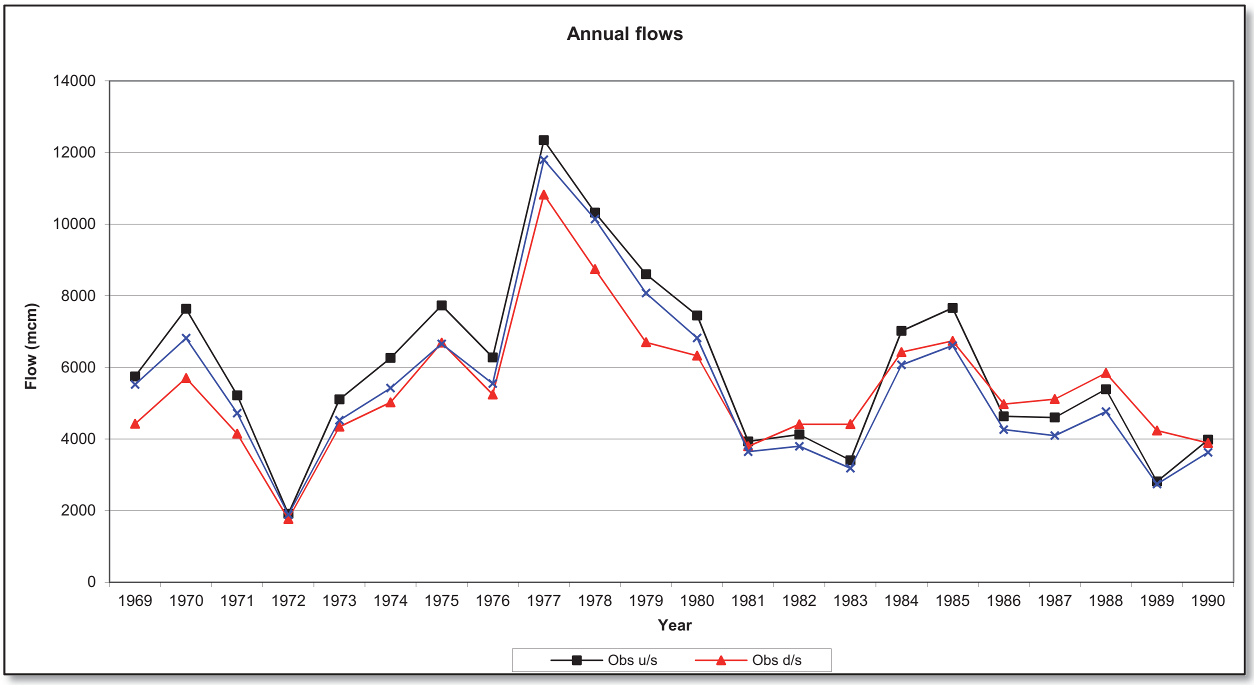


Figure 10.3: Annual Flows

Output is also in tabular form (in file SWAMPF) with a month-by-month summary of flows into and out of the wetland. The output file also contains a summary for the full simulation period, as shown below.

MEAN ANNUAL VOLUMES	
FLOW UPSTREAM OF WETLAND	6006.29
FLOW INTO WETLAND	729.19
LOCAL INFLOW TO WETLAND	940.77
SUPPLY FROM WETLAND/OCD	.00
EVAPORATION FROM WETLAND	1536.80
FLOW OUT OF WETLAND	210.11
FLOW DOWNSTREAM OF WETLAND	5487.21

10.9 Off-channel Storage Dam

Sokhulu Dam was built to supplement the water supply from Lake Nhlabane for Richards Bay Minerals. It is supplied by pumping from the lower Mfolosi River.

10.9.1 Data inputs

The basic data required by the program is listed and described below.

Line1: 1300 0.24 3.0 0.12 14.4 0.75 1.0
Line 2: 5.24 2.4
Line 3: 117 131 148 158 135 126 90 72 54 59 76 95
Line 4: 1932 1994

Line 5: ‘kwamb.mp’
Line 6: 'trig52q’
Line 7: ‘ '

Lines 1 and 2 contain the parameters that are required to simulate an off-channel storage scheme, as follows. They are the same as used to model a wetland but some have slightly different interpretations.

1300	Mean annual precipitation on storage dam (see description of Line 5)
0.24	Surface area of storage dam
3.0	Capacity of storage dam
0.12	Power coefficient of area-volume equation for off-channel dam
14.4	Flow in river below which no diversion takes place
0.75	Proportion of river flow (above threshold) diverted to storage dam
1.0	Proportion of dam volume (above capacity) flowing back to river

Line 2 contains two variables for modelling an off-channel storage scheme, as follows:

5.24	Maximum diversion capacity (set to 0.0 if not applicable)
2.4	Rate of abstraction from wetland/off-channel storage

Line 3 contains the 12 mean monthly evaporations applicable to storage dam (Oct to Sep)
Line 4 contains the first and last years of the period to be simulated
Line 5 contains the rainfall filename. Note that it is a file of monthly rainfalls as percentages of MAP, which gets converted to mm in the program.
Line 6 contains the file of monthly river flow at the diversion point.
Line 7 contains the file of local monthly flows that flow directly into the off-channel dam. If there are no such flows then a blank filename (‘ ‘) is entered.

10.9.2 Model results

As is the case for the wetland, the model produces an output file with a month-by-month summary and a water balance for the full simulation period, as shown below.

MEAN ANNUAL VOLUMES	
FLOW UPSTREAM OF WETLAND	864.47
FLOW INTO WETLAND	42.35
LOCAL INFLOW TO WETLAND	.00
SUPPLY FROM WETLAND/OCD	3.14
EVAPORATION FROM WETLAND	-0.02
FLOW OUT OF WETLAND	9.28
FLOW DOWNSTREAM OF WETLAND	841.41

It is important to note that the diversion into the off-channel dam is not stopped when it reaches full capacity. This may be the case when the dam is fed by a diversion canal, but it would not be true for a pumping scheme. The water balance downstream of the off-channel scheme is, however, correct as all surplus water is immediately spilled back into the river.

11 MODELLING OF STREAMFLOW REDUCTIONS

11.1 Implementation of simplified gush data

11.1.1 Introduction

Appended to the report by Gush et al is a table (hereinafter referred to as the Gush Table) comprising, inter alia, a list of flow reductions for 843 quaternary catchments with an MAP high enough (>650 mm) to sustain commercial afforestation. Flow reductions for both median and low flows are given for 3 tree types (pine, eucalypt & wattle) and 3 depths of soil (shallow, medium & deep). It is envisaged that this data will be incorporated into the SPATSIM platform and database in the version of WRSM/Pitman. Until that stage is reached it will be useful to incorporate the Gush data in a simplified (or smoothed) form, which can be used in the stand-alone model version, i.e. without the SPATSIM platform.

11.1.2 Analysis of Gush Table

The Gush Table was provided in the form of an Excel Workbook, which greatly simplified analysis of the data on flow reductions. In the analysis the following steps were undertaken:

For each quaternary, calculate flow reductions (given in mm units) as percentages of natural hydrology. (In the table, Acocks veld type is given as the natural condition.)
Also for each quaternary, calculate the mean percentage reductions given by the average of the reductions for each soil type.

For each tree type, plot the percentage reductions versus catchment MAP. Two graphs were created, one for median flows and one for low flows.

Inspection of the graphs revealed (a) a distinct difference among the 3 tree types and (b) a trend showing declining percentage reduction with increase of MAP.

In view of the above findings (see step 4) derive (by linear regression) equations relating percentage reduction and MAP for each tree type.

Results of the analysis are summarized in Table 11.1. The minima reflect the minimum percentage reductions (averaged for 3 soil types) for all quaternaries, used to prevent unrealistically low (or negative) reductions when extrapolating to very high MAP. It stands to reason also that the maximum reduction cannot exceed 100%.

The regression equations are in the following format:

$$\text{Flow reduction (\%)} = a - b \times \text{MAP} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11.1)$$

Table 11.1: Results of Linear Regression Analysis

Tree type	Median/Low	Coefficient a	Coefficient b	Minimum
Pine	Median	112.92	0.070	6.0
	Low flow	119.34	0.078	2.9
Eucalypt	Median	120.60	0.064	9.6
	Low flow	128.03	0.054	36.4
Wattle	Median	120.85	0.079	8.2
	Low flow	123.02	0.067	24.8

The plotted data and regression lines are depicted in Figure 11.1 (median flow) and Figure 11.2 (low flow).

The regression equations (and associated minima) are incorporated into the WRSM/Pitman model and are implemented when the user selects the "Smoothed Gush" option. The model also has a "Manual Selection" option, so that user-specified reductions can be entered if so desired. Such reductions can be obtained directly from the full Gush Table or any other source. It is also envisaged that the manual option could be used for sensitivity tests, especially where there is some uncertainty as to the correct reduction figures.

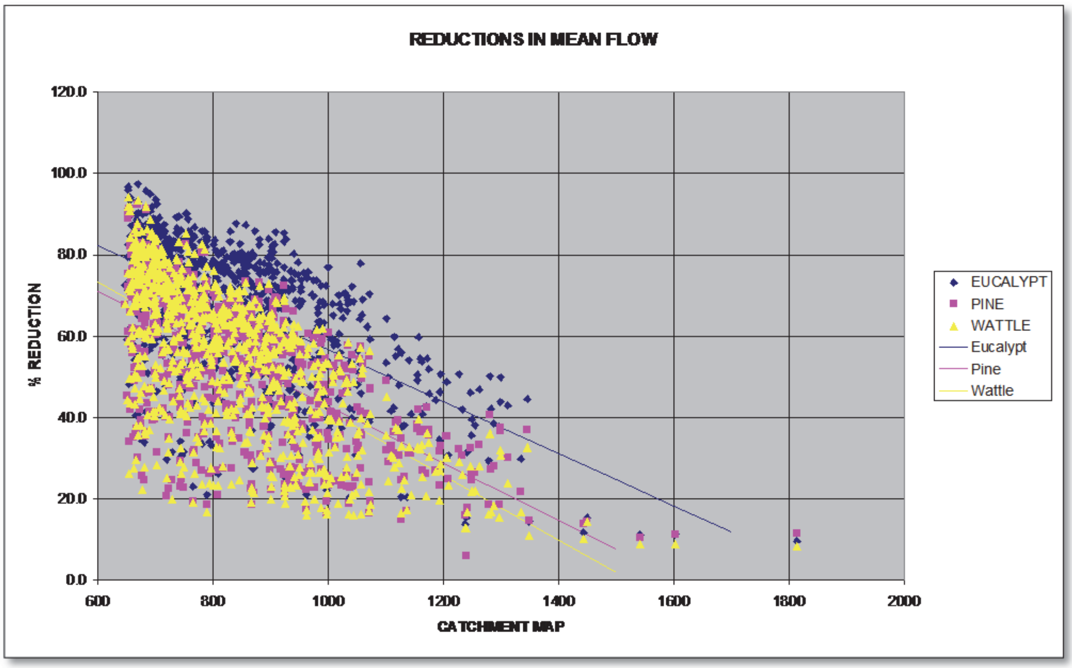


Figure 11.1: Percentage flow reduction versus MAP for median flow

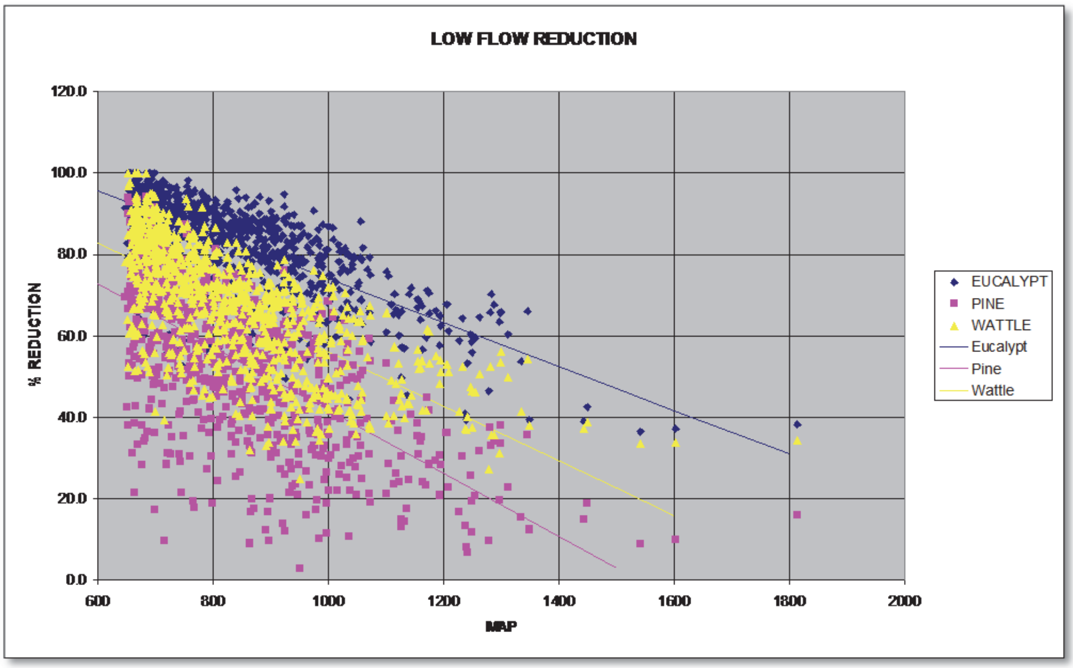


Figure 11.2: Percentage flow reduction versus MAP for low flow

11.2 Application in WRSM/Pitman

As its name indicates, a Stream Flow Reduction area is an area that produces less runoff (or outflow) than it would have produced if it were a Natural area.

Stream Flow Reduction Areas (SFRs) are most easily visualised as wooded areas within a catchment, but it may also be a swath of Alien Vegetation or an area of dense sugar cane. As such, there may be many different SFRs areas within a catchment, each with its own characteristics.

In the past, when WRSM/Pitman was more focussed on surface water modelling, all that mattered was that the final outflows of a catchment matched the observed flows. When there was a forest or a patch of Alien Vegetation in a catchment, all that was necessary was to calculate the amount of water that the vegetation would use and reduce the final outflow of the catchment by that amount.

Now, however, WRSM/Pitman also models the flow of groundwater to some considerable degree, and common sense tells us that since the SFRs are localised, their presence will have a localised effect on the groundwater as well. It also stands to reason that if a forest, for example, intercepts a portion of the precipitation, there will be less water available for infiltration (and hence groundwater recharge) in that area. Once the precipitation has infiltrated, the vegetation will proceed to draw back some of the infiltrated water by evapotranspiration, which will affect the recharge to- and outflow from groundwater, which then affects the final outflow of the wooded area.

In the past, therefore, WRSM/Pitman only had one type of catchment: the 'Normal' or 'Free' catchment. A '**Free catchment'** is **independent** of other catchments. A 'Free catchment' has no influence on any other catchment and cannot be influenced by any other catchment either.

In order to model the localised effects of SFRs, we have come up with the concept of an 'encompassing catchment' (e.g. the total quaternary catchment) within which smaller 'SFR sub-catchments' take up space, produce less runoff than under natural conditions and so reduce the total runoff of the 'encompassing catchment'.

Because they are part of the 'encompassing catchment', the SFR sub-catchments share most (but not all) of the model parameters with the 'encompassing catchment' in which they lie.

Conversely, the area of the 'encompassing catchment' would grow and shrink as the areas of the 'SFR sub-catchments' within its borders grow and shrink, to maintain a constant area for the catchment as a whole.

To show that an '**encompassing catchment**' is in charge – at least as far as simulation parameters are concerned – we decided to call such a catchment a '**Parent catchment**'.

Since all 'SFR sub-catchments' within a Parent catchment are subordinate to that Parent catchments, we decided to call an '**SFR sub-catchment**' a '**Child catchment'**.

If a catchment is **neither a Parent nor a Child**, we call this catchment a '**Free catchment**'

The Parent and Child nomenclature describes the way in which the catchment types act, react and interact with one another very well, and should therefore be taken with a pinch of humour. The following rules apply to the three types of runoff module or catchment:

1. All catchments are created as 'Free' catchments.
   A Free catchment is neither a Parent nor a Child.
   A Free catchment has the potential to become either a Parent or a Child.

2. Any Free catchment can be 'elevated' to the status of Parent catchment.
   A Parent catchment can capture Child catchments to become part of itself.
   A Parent catchment can free any Child catchment that it does not need any more
   A Parent catchment cannot be captured by another Parent catchment.

3. A Parent catchment can be told to 'capture' a Free catchment as a Child:

A Child cannot be captured by more than one Parent.
A Child takes on parameters of its Parent only.
A Child only runs when told to do so by its Parent.
A Child contributes its Runoff to the outflow of the Parent.
When freed by its Parent, a Child reverts to a 'Free' catchment.

4. A Parent catchment can be changed to a 'Free' catchment only once it has freed all its Children.

Although, for now, our Child catchments only deal with SFRs areas, this concept could be broadened later to cover Stream Flow Enhancing areas (such as paved areas) as well, since these areas, too, have an influence on groundwater.

So far, WRSM/Pitman has been programmed to create Child catchments (i.e. runoff modules) to handle SFRs due to afforestation and alien vegetation. The method used to determine the impact on the hydrological cycle is by the adjustment of certain model parameters, as follows.

- PI – the interception storage in mm;
- FF – the factor by which potential evapotranspiration is increased;
- SL – the soil moisture storage below which runoff ceases and
- ST – the total soil moisture capacity.

Adjustment of these parameters is done to reflect the following changes wrought by the introduction of forests or alien vegetation :

- increased interception due to greater leaf area, etc.;
- deeper penetration of tree roots and
- increased evapotranspiration (analogous to crop factor effect).

Reductions in runoff are generally expressed as percentage reductions in mean (i.e. MAR) and low flows, the latter being the average flows in the lowest quartile.

Information obtained from tests on a selection of catchments covering a wide range of climates was used to determine the following relationships between flow reductions and parameter adjustments:

$$\text{MAR reduction (\%)} = A\,.\,\Delta PI + B\,.\,\Delta FF + C\,.\,\Delta SL \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11.2)$$

$$\text{Low flow reduction (\%)} = X\,.\,\Delta PI + Y\,.\,\Delta FF + Z\,.\,\Delta SL \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11.3)$$

In order to enable solution of the above equations a predetermined relationship between ∆PI and ∆FF was assumed and it was also assumed that ∆SL and ∆ST were the same. The constants A,B,C and X,Y,Z are different for each catchment and depend on MAP and ST.

As the above equations do not give an exact result they are used to perform a number of iterations until the closing error is within acceptable limits.

IMPORTANT NOTE

The equations relating flow reductions to changes in model parameters were derived from analyses of catchments suitable for afforestation. Such catchments are located in the wetter parts of South Africa, where the model parameter FT is greater than zero. If FT is zero the equations definitely do not apply. In the (very unlikely) situation of afforestation in a catchment with zero FT one should never try to model the SFR using a Child catchment. The same applies to catchments with alien vegetation. However, as it is more likely for alien vegetation to spread to relatively dry areas where zero values of FT are appropriate. In such cases it will also be necessary to model the impacts on streamflow without a Child module. This should not present any serious problem as, in such catchments, the baseflow proportion of total flow (as derived from groundwater) is usually negligible.

In both the above cases, the user cannot obtain either groundwater plots or groundwater time series output because the model does not differentiate between surface and groundwater flow when subtracting the flow due to afforestation and/or alien vegetation. If the user attempts to obtain either, the outputs (plot and/or time series) will be zero.

12 ALIEN VEGETATION (WR2005 STUDY) INVASIVE ALIEN VEGETATION AND DAM YIELDS – ILLUSTRATING THE IMPACT OF CLEARING PROGRAMMES ON ASSURANCE OF SUPPLY BY DR D LE MAITTRE

Authors: David Le Maitre[1] and André Görgens[2,3].
With contributions from Mandla Mehlomakulu[1], Johan van Rensburg[2], Arthur Chapman[1], Dave Scott[1] and Brian van Wilgen[1].

The following chapters were extracted from the above report: Chapter 3 Methodology up to section 3.3 (inclusive).

12.1 Methodology

The methodology employed in this study comprised six stages:

- quantifying current levels of infestation;
- projecting future (10 years) levels of infestation;
- formulating a suitable proportional streamflow reduction model for each selected catchment system;
- estimating the respective streamflow sequences for natural, current-level invaded and future-level invaded scenarios via catchment modelling, linked to the streamflow reduction models;
- determining the yields at a range of assurance levels deliverable from a range of hypothetical impoundment sizes for each invasion scenario via reservoir water balance modelling and
- determining the incremental reductions in yields, from natural, for the range of cases analysed.

In the interests of clarity (and economy of effort), it was necessary to ignore all existing human-derived impacts in the selected catchments. In this way, the estimated streamflow reductions due to alien plants could be clearly illustrated, not confounded with the effects of other physical developments on the streamflow regimes of catchments. All alien plant-related impacts were therefore juxtaposed with naturalised streamflows. The generation of these natural streamflows and of the impacts is explained in Section 19.4 below.

12.2 Mapping of Alien Plant Invasions

The data on the extent, density and composition of alien plant invasions was extracted from the databases prepared for each of the management plans. The mapping methods differed between the catchments and this is described below

Sonderend

The catchment was mapped by fieldworkers onto standard 1:50 000 base maps following the procedures and standards set up by Le Maitre and Versfeld (1994) and the data standards developed for the Working for Water Programme (Muller et al. 1999). The species composition was recorded as the percentage canopy cover class for each species. Each mapped area was identified as riparian or non-riparian except in the catchment above the Theewaterskloof Dam where the riparian polygons were not distinguished. The area of the riparian invasions in this portion of the catchment was estimated from the invasions of the species in these polygons which are known to be primarily riparian invaders.

Upper Wilge

The catchment was mapped with a combination of field work, using 1:50 000 base maps, and high resolution video imagery which was interpreted onto base maps and verified with field work (Bailey et al., 1997). The field data were mapped according to the Working for Water standards (Muller et al. 1999). The video data were mapped as species or species combinations with the specified density classes. The mean proportion of the total cover value was given was for each species in the species combinations so that the data could be converted to the specified standard. Riparian and landscape polygons were not distinguished so the area of riparian invasions was estimated from the estimated width of the invaded strip along the rivers and data on the total length of river invaded in each quaternary catchment.

Upper Umgeni

Only a strip 60 m wide (30 m either side) of the rivers in these catchments was mapped onto base maps from high resolution video images (MBB 1997). No non-riparian areas were mapped. The length and density (sparse, medium, dense) of the invaded sections was recorded and the frequency of the different species was summarised. These data were converted to the percentage cover based on this data and information received from Kevin Meier (LRI pers. comm. 2000) who did the original modelling of the alien vegetation water-use using the ACRU model (MBB 1997).

Sabie-Sand

The catchment was mapped via fieldwork onto 1:10 000 and 1:50 000 base maps according to the Working for Water standards (Muller et al. 1999, Nel et al. 1999). The invasions within the plantation compartments were not recorded as these species are typically understorey species and may not have a significant impact on the total water-use. Almost all the invaded areas were in riparian habitats so landscape invasions were analysed and modelled as part of the riparian invasions.

12.3 Modelling of invasions for management plans

This section describes the approach and methods used to estimate the increase in the extent and density of alien plants in each of the catchment areas included in this analysis. The overall approach followed that developed by Versfeld et al. (1998, Appendix 7) with the details differing between the different catchment areas depending on the state of the invasions and the nature of the mapping. Two types of invasions were recognised throughout this study: riparian invasions which occur along watercourses and non-riparian or landscape invasions which occur in dryland areas. The two categories were chosen because (Versfeld et al. 1998, Le Maitre et al. 2000): (a) the freely available water in riparian areas will allow invading shrubs and trees to use more water than in the landscape situation especially in the dry season; and (b) the species composition in riparian and landscape habitats often differs, particularly in the lower rainfall areas. Riparian areas (habitats) are known worldwide to be particularly susceptible to invasions; they are invaded by a wide range of species and invasions can be very rapid.

12.3.1 Modelling approach

In this study we have used an approach which was developed for catchment management plans prepared for the Working for Water Programme (Versfeld et al. 1998, Appendix 7). Invasion processes can be divided into two phases: (a) expansion via dispersal (spread) which results in an increase in the total area invaded, and (b) densification, i.e. an ongoing increase in the density of the invading species. Expansion can be characterised by a sigmoid curve with a slow initial expansion, a rapid increase in the middle and a slowing down as the available area decreases. This is conveniently represented by the discrete form of the logistic growth function:

$$Nt = Nt - 1 + r\left(1 - Nt - \frac{1}{K}\right)Nt - 1 \qquad \text{……………………………………………………..(12.1)}$$

where Nt is the area at time step t, r is the rate of increase and K is the potentially invadable area (ha)

Expansion rates (r) generally range from 0.10 to 0.30 per year but for this study a conservative value of 0.10 was used for expansion and for increases in density (see below). A similar approach was used to estimate the expansion rates in riparian areas with the unit being a kilometre rather than the hectare used for landscape invasions (Versfeld et al. 1997).

Density increases also begin slowly and then rise non-linearly but there is no indication that the rate slows as stands become denser. This phase is characterised by the discrete form of a simple exponential growth function:

$$\mathrm{Pt} = \mathrm{Pt} - 1 + \mathrm{rPt} - 1 \qquad (12.2)$$

Where

P = percentage cover; t=the current time step; $_{t-1}$=the previous time step; and r=the rate of increase in cover.

All newly invaded areas are given an initial cover of 1.0%. The species composition, i.e. the relative importance of each species, was assumed to remain constant for the projections of both the extent and the composition of the future invasions. The modelling of expansions assumes that the rate of increase in area matches the rate of increase in density in the existing invaded areas so that the mean density remains constant.

12.3.2 Land-cover and use

Land-cover and use is important for predicting landscape invasion patterns and certain land-uses and land-covers (vegetation types) are less susceptible to invasion than others. For this study we grouped the land-cover classes defined for the National Land Cover (Thompson 1996; Fairbanks et al., 2000) according to their susceptibility to invasion (Table 12.2). Natural vegetation and pasture is regarded as being susceptible to invasion but urban areas, cultivated lands, plantations and the like are excluded from invasions. Riparian invasions are assumed to increase without regard to the adjacent land cover types as there seem to be few, if any, limits on invasions of these habitats. The total area of the invisible land cover classes, both invaded and uninvaded, was used as the potentially invadable area for modelling the projected invasions. The model is therefore a 'lumped' one and does not take into account the effects of the spatial distribution of the invaded and potentially invasible areas. This is one of the key reasons for adopting conservative values of 0.10 for the rate of expansion and density increase. The potential rates estimated from the invadable area or river length, using the relationship developed by Versfeld et al. (1998), were generally substantially higher (0.15-0.25).

12.3.3 Projecting the future state of invasions

Alien plant invasions are not static but will change with time. Three scenarios have been investigated: (a) pre-invasion conditions, (b) the current state and (c) a future invaded state in 10 years' time assuming that no control operations take place. The state of invasions of the catchments differed, so the modelling approach was adapted to take this into account, as described below.

In the Sonderend catchment the invasions are already extensive, with a mean of 80% of the landscape and 82% of the river length in some quaternary catchments being invaded to some degree of density. This places the invasions at the top end of the logistic growth curve and the resulting expansion is slow. In this situation it is unreasonable to assume that the mean density will remain constant. A second scenario was therefore developed which allows for a 50% increase in the mean density of the invasions over the 10 year period. The density increase is conservative compared with the doubling in density which would occur if the density increase was 10% per year but allows also for the limited expansions. In the Upper Wilge catchment the expansions were modelled without any additional increase in density as the degree of invasion in these catchments is relatively low. In the Upper Umgeni only the increase in the extent (length) of the riparian invasions was modelled and the data were converted to areas using the width of 30 m either side of the river as used in the original mapping and modelling study (MBB 1997). In the Sabie-Sand catchments the invasions were almost entirely riparian and all the invadable areas were already invaded to some extent (Nel et al., 1999). Therefore only the increase in density was modelled.

12.3.4 Output data

All the data were expressed as the condensed or the equivalent dense area, i.e. if the mean canopy cover of an alien species on an area 100 ha is 25% then the equivalent dense area is 25 ha. This allows the stand to be treated as a dense stand for flow-reduction modelling purposes as well as simplifying the calculation of invaded areas. This assumes that the relationship between flow reductions and canopy cover over the range from low cover to canopy closure is linear. This relationship is probably non-linear, but the development of a generalised relationship between canopy cover and structure and the effects on flow reductions falls outside the scope of this limited study.

The condensed area data for the individual species were summarised using the “biomass” classification developed by Versfeld et al. (1998, Table 12.3). This groups species into either: tall trees, medium trees or tall shrubs based on: (a) their size and structure as mature plants, (b) whether they are deciduous or evergreen and (c) what is known of the relative impacts on streamflow and water-use of the main commercial plantation species (pines, eucalypts, see Scott et al. 1998).

12.4 Impacts on Streamflows

12.4.1 Streamflow and other hydrological information

Given the limited budget and time-frame of this study, it was necessary to restrict both the degree of manipulation of original or “raw” hydrological information for and the scale of discretisation of the selected catchments. Therefore, the whole study was based on a spatial resolution of quaternary catchments and on readily prepared information from the WR90 national water resources survey published by the Water Research Commission (Midgley et al. 1994). This approach enabled the use of a well-prepared and internally consistent set of information for each of the study catchments. For each quaternary catchment 70 year sequences of monthly rainfall were extracted from the data sets on the WR90 CD-ROM, as were mean monthly evaporation values and catchment model parameters. (The parameters for the Pitman model had been determined on a regionalised basis by the WR90 team through an elaborate process of catchment model calibration and verification, with full recognition of the historical human-derived impacts at the quaternary catchment scale.) Quaternary catchment streamflow sequences, for both natural and invaded scenarios and each 70 years in length, were then generated by means of the catchment model, as described in section 3.4 below.

12.4.2 Streamflow reduction calculations

The impacts on streamflow were calculated using revised versions of the age-biomass models for the different growth form categories (Table 12.3) and a proportional flow reduction model for the relationship between biomass and flow reductions. These age-biomass models were linked to a monthly catchment model, as described in Section 3.4 below.

12.4.3 Revised age and biomass models

The relationship between biomass and age for tall trees was developed using data on the biomass of 29 and 40 year old stands of Pinus radiata at Jonkershoek (Van Laar and Van Lill, 1978, Van Laar 1983) and data from a Pinus radiata height growth model parameterised using stand measurements from the Bosboukloof catchment (Le Maitre and Versfeld 1997). The height data were used to scale the biomass data for different stand ages. The scaled data on biomass at different ages were then used to develop the following sigmoid biomass growth curve for the pine stand:

$$\text{Pine biomass (t/ha)} \quad = 300/(1 + \mathrm{e}^{3.67947} \text{ x Age in years}^{-1.4109}) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12.3)$$

$$r^2=0.96,\ n=9,\ P < 0.01$$

The relationships between biomass and age for medium trees and tall shrubs (Table 12.3) developed by Le Maitre et al. (1996) were also recalculated. Data on biomass and age for medium trees were obtained from Milton and Siegfried (1981) and tested with different regression models. The high biomass of young stands was matched most closely by a log regression model which gave the following relationship, which is essentially the same as the one used by Le Maitre et al. (1996):

$$\text{Medium tree biomass (t/ha)} = 96.0732 \times \log_{10}(\text{Age in years}) - 4.8081 \;\ldots\ldots\ldots\ldots(12.4)$$

$$r^2=0.98,\ n=4,\ P=0.01$$

The biomass model for tall shrubs was developed by fitting a model to data on the age and biomass of fynbos from Kruger (1977) and Van Wilgen (1982). The only data available for the biomass of a tall shrub invaded stand are for a single, 9-year old Hakea stand (Van WIlgen et al. (1985). The sigmoid model for fynbos biomass was adjusted by altering the asymptote of the fitted model so that the predicted biomass at an age of 9-years matched that of the Hakea stand. This adjustment does not affect the other parameters. The final relationship is as follows:

$$\text{Tall shrub biomass (t/ha)}= 76/(1+\mathrm{e}^{3.1868} \text{ x Age in years}^{-1.35973}) \;\ldots\ldots\ldots\ldots\ldots\ldots(12.5)$$

$$r^2=0.68,\ n=12,\ P <0.01$$

The adjusted model now tends to a maximum biomass of about 76 tons per ha compared with the maximum of 40 tons per ha estimated for uninvaded fynbos.

12.4.4 Biomass and flow reduction

One of the complications inherent to this approach is that the flow reductions should represent the incremental flow reduction compared with a baseline state. In the case of the fynbos catchments the baseline state for the reduction is the post-fire condition where the evaporation is primarily from the soil and from resprouting plants with a low biomass (Bosch et al. 198#). The baseline in the afforested catchments was fynbos with a mixture of tall, proteoid shrublands and shorter vegetation (Rycroft 1945). The age of the fynbos was not recorded at the time but was about 19 years in the upper part of Biesievlei and about 6 years old in the lower part of the catchment (Van Wyk 1977). Assuming a mean age of 14 years, the estimated biomass of the fynbos would be about 21.4 tons/ha, equivalent to a reduction of about 0.6% of the annual runoff and 3.2% of the low flow. These values are low compared with the impacts of the plantations and well within the likely errors in the estimates; therefore the additional complications of estimating the incremental biomass were omitted from this analysis.

An analysis of the impacts of plantations on streamflow by Scott and Smith (1997) identified two forms of flow reduction curves: (a) a long lag before a significant reduction in flow as recorded in Jonkershoek and Cathedral Peak catchments; and (b) a short lag as recorded for the Mokobulaan and Westfalia catchments. This distinction has been maintained in the development of these models with Biesievlei (Pinus radiata, Jonkershoek) and Westfalia D (Eucalyptus grandis) being selected as the two catchments for model development.

12.4.5 Long lag curves

The biomass model for a Pinus radiata stand (see above) was used to estimate the stand biomass at different ages in the Biesievlei catchment from data on the height growth of the stand (Le Maitre and Versfeld 1997). The pine biomass estimates were then regressed against the estimated percentage reductions in annual and low flows recorded for the Biesievlei catchment (Scott et al. in prep). A sigmoid relationship was evident in the raw data so this form of model was used in the regression analysis. The initial regression models gave relatively high reductions (>10%) in the first and second years. An inspection of the data showed that the first two years after the planting of Biesievlei were relatively dry years. This resulted in the expected runoff values being reduced and, thus, in an overestimate of the reductions compared to later years. The values for the first two years were reduced by inspection to match the expected shape of the overall relationship. The regression analysis was repeated and the new model's predictions were much lower for the first few years. The new model of the long-lag relationship between biomass and annual flow reductions is as follows:

$$\text{Annual flow reduction (\%)} = 75/(1 + e^{14.2216} \text{ x biomass (t/ha)}^{-2.9194}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (12.6)$$

$r^2=0.83$, $n=34$, $P<0.01$

A similar procedure was used to develop a regression model of the relationship between the percentage low flow reduction and biomass:

$$\text{Low flow reduction (\%)} = 100/(1+e^{10.0252} \text{ x biomass}^{-2.0927}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12.7)$$

$r^2=0.68$, $n=34$, $P<0.01$

12.4.6 Short lag curves

A biomass model was developed for Eucalyptus grandis (Le Maitre unpubl.) and regressed against the observed annual flow reductions in Wesfalia catchment D (Scott et al. in prep) and estimates of the low flow reductions (D. Scott unpublished). The initial regression models for annual and low flow reductions predicted high impacts (>15% and >25% respectively) in the first year after planting. As described earlier for Biesievlei, the impacts of the plantations at Westfalia were influenced by marked cycles in rainfall which lasted for several years. In this case they resulted in high estimates of the flow reductions in the first year after planting: 13.6 and 9.1% for annual and low flow respectively. New models were fitted using the adjusted values for the first year after planting and gave the following relationships:

$\text{Annual flow reduction (\%)} = 100/(1+e^{2.2958}\ \text{x}\ e^{\text{Biomass[t/ha]} \times -0.02388})$ …………………(12.8)
$r^2=0.86, n=13, P < 0.01$
$\text{Low flow reduction (\%)}=100/(1+e^{1.9677}\ \text{x}\ e^{\text{Biomass[t/ha]} \times -0.02474})$ ………………………..(12.9)
$r^2=0.68, n=10, P < 0.01$

12.4.7 Setting-up the flow-reduction models

These models can be scaled by adjusting the asymptote (numerator). They can be converted directly to proportional flow reduction models by changing the asymptote to the maximum proportional flow reduction that is expected. Because the data used to develop these models included percentage reductions much higher than the expected asymptotic values, both the short and long lag curves of these models do not reach 100% reductions when using the tall tree biomass function for ages up to 40 years. To reach the percentage reductions suggested in Table 12.4 these functions need to be scaled using the following values for the asymptote (numerator):

- Long lag annual flow reductions : 115
- Long lag low flow reductions : 122
- Short-lag annual flow reductions : 103
- Short lag low flow reductions : 102

To get predicted reductions as proportions (i.e. % ÷ 100) of the flow, the asymptote's value should be divided by 100.

12.4.8 Calculating flow reductions

The new annual and low flow reduction models (see above) were used in conjunction with the models for the biomass and age to calculate the flow reductions for each of the biomass classes (tall trees, medium trees and tall shrubs) in stands of different ages. The values for each age in years were averaged to give the mean annual and low flow reductions (as a fraction) for stand of different mean ages. For example, if the mean age is 20 years and there is an equal area in each age class then the mean flow reduction is the mean of the age-specific annual or low flow reductions for stands of 1-40 years of age.

The models were applied to landscape invasions as described above using the generated naturalised runoff for each quaternary catchment as the available flow and the suggested maximum percentage reduction (Table 12.4). Riparian situations are more complex because the invader's root systems can tap either into lateral drainage towards the watercourse or water drawn from the surface water flowing in the watercourse itself or both. Thus the potential flow reduction in an invaded area in the riparian zone can exceed the available mean annual runoff (MAR) for the catchment if the available energy does not limit evaporation to less than the MAR. The suggested maximum flow reduction (asymptote in mm in Table 12.4) for the catchment was used to calculate the potential reduction as a proportion of the naturalised runoff of each quaternary catchment. This was multiplied by the scaling value suggested above to give the final asymptote (numerator) for the flow reduction equations when applied to riparian invasions.

Table 12.1: Basic data on the different catchment areas selected for this study.

Catchment	Catchments	Area (km^2)	Climate (mm)	Vegetation and land-cover
Sonderend	Tertiary H60	3371,1	MAP: 361-1895 MAR: 41-1207	Fynbos and renosterveld (68%); dryland cultivation and irrigated land
Upper Wilge	Tertiary C81	6160,4	MAP: 612-892 MAR: 34-150	Grassland used as natural pasture (61%); dryland cultivation
Upper Mgeni (Midmar)	Quaternaries U20A-U20C	925,1	MAP: 932-1010 MAR: 184-290	Grassland used as natural pasture, plantations, irrigated areas and dryland cultivation
Sabie-Sand	Secondary X3	6321,8	MAP: 460-1334 MAR: 4-543	Bushveld, grassland and forest (46%); commercial plantations, irrigated agriculture and dry land cultivation (subsistence)

The catchment areas and climatic data were obtained from the data bases for quaternary catchments prepared for the WR90 study (Midgley et al. 1994). The summary of the land cover data was obtained from reports on the catchments (see the text).

MAP = mean annual precipitation; MAR = mean annual runoff .

Table 12.2: A summary of the invasibility of the different land-cover classes used for the National Land Cover Survey (Thompson 1996)

Invasibility for landscape invasions	Land Cover Class
Not invasible	All classes of Urban / built-up land Mines and Quarries All classes of Cultivated land Forest plantations Water bodies Barren Rock
Invasible	All classes of natural vegetation Dongas & sheet erosion scars Wetlands All classes of Degraded land Improved and Unimproved Grassland

Wetlands are assumed to be invasible as most wetlands are seasonal dry, or have extensive seasonally dry areas which are subject to invasions in contrast to the permanently wet areas mapped as waterbodies. The areas involved are generally also small and unlikely to significantly influence the results.

Table 12.3: Alien species and associated biomass equations used in calculating the impact of invaders on water resources (after Versfeld et al. 1998)

Invading Alien Species	Biomass Equation No.	Invading Alien Species	Biomass Equation No.
Acacia baileyana	2	Leptospermum laevigatum	1
Acacia cyclops	2	Melia azedarach #	2
Acacia decurrens	2	Morus alba #	2
Acacia elata	3	Nerium oleander	2
Acacia longifolia	2	Opuntia spp	1
Acacia mearnsii	3	Paraserianthes lophantha	1
Acacia melanoxylon	3	Pinus spp	3
Acacia pycnantha	2	Pittosporum undulatum	1
Acacia saligna	2	Populus spp #	3
Acacia spp	3	Prosopis spp	2
Alnus viridis	3	Psidium guajava	1
Arundo donax	2	Pyracantha sp	1
Caesalpinia decapetala	1	Quercus robur #	2
Chromolaena odorata	1	Robinia pseudoacacia #	2
Cupressus glabra	2	Rubus Sp	1
Eucalyptus spp	3	Salix spp #	2

Invading Alien Species	Biomass Equation No.	Invading Alien Species	Biomass Equation No.
Ficus spp	3	Sesbania punicea	2
Gleditsia triacanthos #	2	Solanum mauritianum	1
Hakea spp	1	Tamarix spp	2
Jacaranda mimosifolia #	2	Uncertain	3
Lantana camara	1	Uncertain	3

Deciduous species are indicated with a #. For more information see the text.

Table 12.4: Values for parameters of the flow reduction equations for the different catchments, landscape and riparian invasions and annual and low flows

Catchment	Situation	Flow period	Suggested Asymptote		Mean age (years)
			(%)	(mm)	
Sonderend	landscape	annual	83		7.5
		low flow	85		7.5
	riparian	annual	100	500	20
		low flow	100	30	20
Upper Wilge	landscape	annual	100		20
		low flow	100		20
	riparian	annual	100	300	20
		low flow	100	6	20
Upper Mngeni	landscape	annual	90		20
		low flow	95		20
	riparian	annual	100	400	20
		low flow	100	20	20
Sabie-Sand	landscape	annual	90		20
		low flow	95		20
	riparian	annual	100	500	20
		low flow	100	35	20

*Note: The low flow values represent the expected cumulative reduction over three low flow months that occur in the average year. The values for the suggested maximum percentage and absolute reductions were selected to match the growing conditions in the different catchments. The mean age of the invaders in the different situations was based on the estimates of Versfeld et al. (1998).

12.5 Special Notes On Alien Vegetation In The Riparian Zone

12.5.1 Outline of Methodology

The basic assumptions and calculation steps are summarized in bullet form below.

- vegetation in riparian zone has access to additional water, i.e. seepage to or from the stream channel;
- alien vegetation is first modelled as if not in riparian zone, then further adjustments are made to account for additional water loss, as follows;
- for each month, calculate actual evapotranspiration and compare with the potential rate;
- the difference between actual and potential represents the remaining "crop demand" of the alien vegetation and
- when converted to a volume, this difference gives the (potential) additional water loss, which is subtracted from the residual runoff from the portion of catchment in the riparian zone that is covered by alien vegetation.

12.5.2 Modelling Procedure

The runoff module in WRSM/Pitman uses a number of extra variables to calculate the additional water use by riparian alien vegetation, as described below. (Note that the calculations are performed after the effect of alien vegetation is determined as if all is in the non-riparian zone.)

Let

$\text{EAVE} = \text{Actual evaporation (mm) for month}$
$\text{ETDEF} = \text{Difference between Potential \& Actual evaporation (mm) for month}$
$\text{PRIP} = \text{Proportion of alien vegetation area in riparian zone}$
$\text{ETVOL} = \text{ETDEF expressed as volume for riparian zone}$

There is also an existing variable, PEACT, which is the Potential evaporation for the month in mm. A further variable, AREA (km²), is the area of the "Child" module representing all the alien vegetation in the catchment. Total Outflow (million cubic metres) is the computed flow from the "Child" catchment to be adjusted for additional riparian losses.

ETDEF is calculated as follows. (Note that difference between potential and actual evaporation for the month can't be negative so check and set = 0 if so.)

$$\text{ETDEF} = \text{AMAX1}\,(\,0.0\,,\,\text{PEACT} - \text{EAVE}) \quad \ldots\ldots(12.10)$$

Now try to satisfy evaporation deficit in riparian zone from streamflow.

$$\text{ETVOL} = 0.001 \times \text{ETDEF} \times \text{PRIP} \times \text{AREA} \quad \ldots\ldots(12.11)$$

The final step is to subtract ETVOL from TotalOutflow (or set it to zero if ETVOL is greater than TotalOutflow) as follows:

$$\text{TotalOutflow} \quad = \text{AMAX1}\ (0.0\ ,\ \text{TotalOutflow} - \text{ETVOL}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(12.12)$$

13 MINE (WITH 2005 ENHANCEMENTS) COLEMAN/P VAN ROOYEN

Note: Only the **quantity coding** was taken from this document for WR2005.

13.1 Mine Module

13.1.1 General Description of Mine Water Circuit

A typical mining operation can consist of underground mining (high extraction and/or bord-and-pillar) opencast mining, a coal washing plant, discard and slurry dumps, pollution control dams and isolated polluted areas. A generic layout was formulated into which the coal mining operations assessed during the situation assessment can be represented. The generic layout is shown in Figure 13.1.

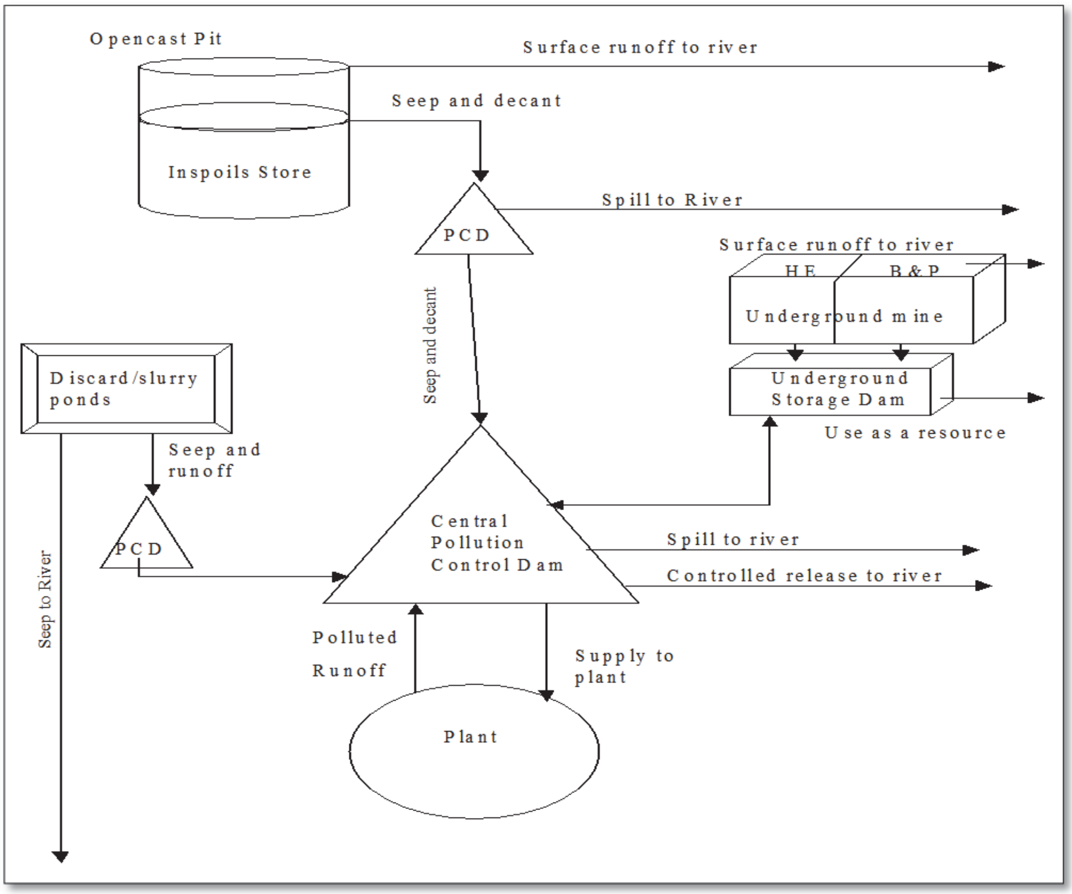


Figure 13.1: Generic Coal Mine Water Modelling System

A coal mine water circuit generally consists of two circuits or systems. A system that supplies the domestic or potable demands of the mine complex and deals with the sewage effluent produced on the mine. Potable water is used on the mine complex for the villages, offices and workshops. Many of the mines have their own water treatment plants to produce the required potable water. The raw water for this circuit can be abstracted from a borehole, a river or dam, supplied from Eskom, or supplied by a municipality. The mines generally have sewage treatment plants (STP) on the complex to deal with the sewerage. The effluent from the STP can be used for irrigation, dust suppression, or released to the river system as a point source. This circuit is treated in the water quality model as an abstraction and a point source return flow via the STP.

The other circuit on a mine complex is the polluted water circuit. The water in the dirty water circuit could include runoff from dirty catchment areas collected in pollution control dams, the return water from a slurry disposal facility, decant or water make from an opencast pit and water pumped from underground. A sub-module has been developed for an opencast pit, an underground mining section, a dirty catchment area and dumps. These outputs from these modules are connected as per Figure 13.1 to represent a particular coal mine. The generic layout of the polluted water circuit is shown in Figure 13.1.

Figure 13.1 shows, for illustrative purposes only, a single opencast pit and underground mining section. However provision has been made in the model for up to 10 pits, 10 underground section and 10 dumps for a particular mine complex.

The coal beneficiation plant is the main water demand centre on a coal complex. The plant is often supplied with recycled polluted water from the mines polluted water circuit with make-up water perhaps being supplied from the potable water circuit. The quantity of water used at the plant is a function of the coal throughput and the type of beneficiation process employed at the plant. A time series of water demands are input to the model over the simulation period. These demands being met with water from the central pollution control dam.

Practically on a mine complex, there are a number of pollution control dams (PCD). In the generic representation of the complex these have been lumped into a single pollution control dam called the central pollution control dam. This PCD receives water from the underground mine section, the opencast section, the discard dump/slurry pond (PCD) and polluted runoff from the dirty areas on the complex. Allowance has been made for the water stored in the central PCD to be pumped underground. This management option is practiced on some mines.

13.2 Opencast Sub-module

13.2.1 Introduction

An opencast mining operation is complex in terms of the mining plan, water pathways and water quality. Detailed models are available for modelling the water quality and water make of an opencast pit. However, given that the WRPM is a planning model, the detailed description of the mining process used in these models is not necessary to describe the general behaviour of a pit. The information collected on the opencast mining operations during the situation assessment included:-

- the reserve area for the different pits on a particular mine complex;
- the start and end date of the mining operation on each of the pits;
- the current area mined;
- details of the current and future rehabilitation;
- the decant level and final storage volume after closure and
- when available, the closure plans for the pits.

The opencast component of the mine module was formulated so that the opencast pit model can accommodate the different configurations found on the various mines in the catchment. An opencast mine can essentially be in three states viz.:-

- pre-mining that is in an undisturbed or natural state;
- operational pit and
- post mining, i.e. a closed pit.

The model has been formulated so that all three states can be included in a single model framework.

13.2.2 Structure of model

During the life of mine of a pit, the opencast mine could consist of the following components (See Figure 13.2):-

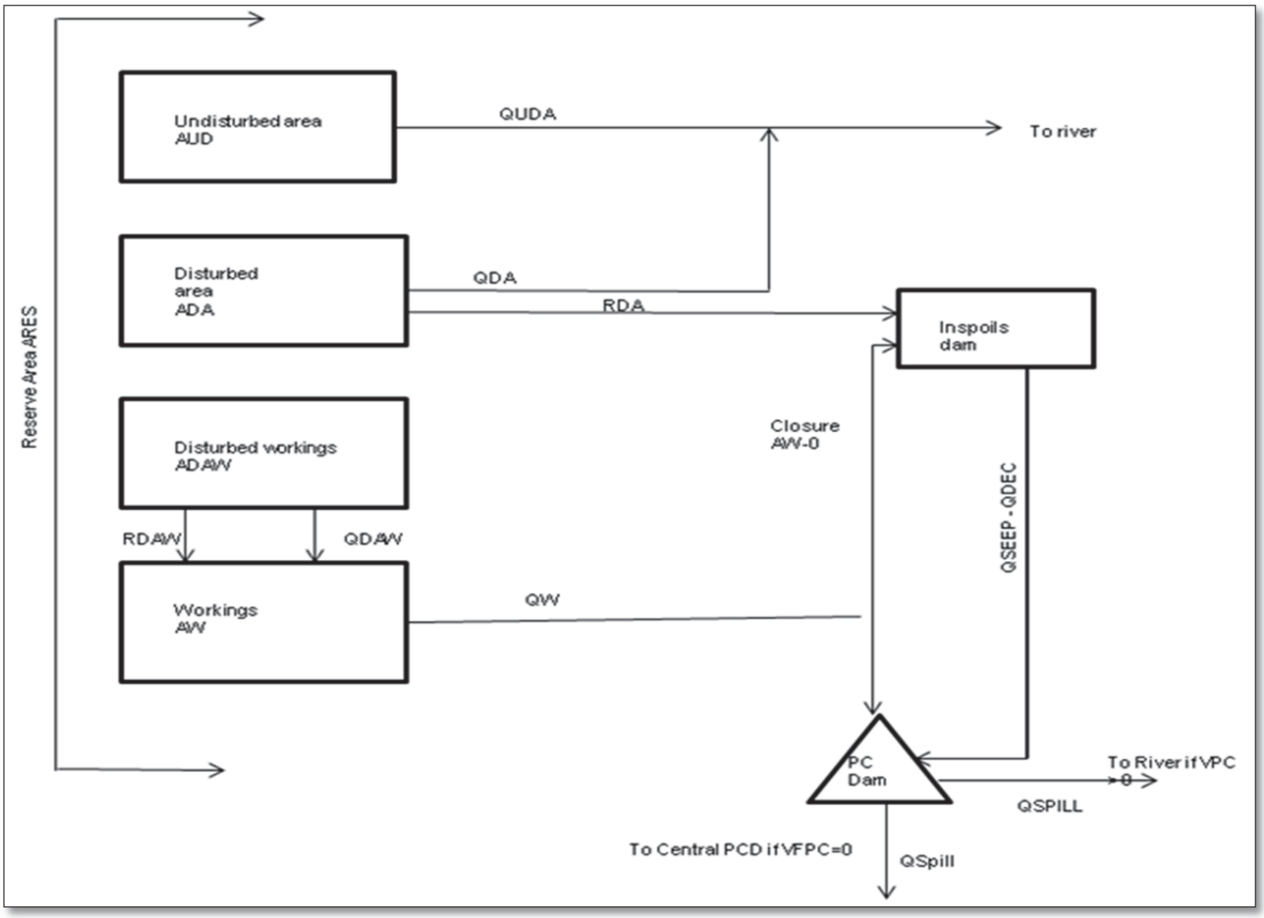


Figure 13.2: Flows Path for Opencast Sub-module

Working Area (Workings): The working area of the pit is the area from which the coal is being abstracted. The area of the opening is generally constant over the life of the mine. This open area can receive direct rainfall, recharge through the spoils body and surface runoff. The extent to which the workings receive recharge and surface runoff depends on the stormwater management, floor contours, surface contours, mining approach and the rehabilitation practices at the pit. The water that accumulates in the pit from these sources is generally pumped to a pollution control dam (PCD) so that the mining operations can continue. In the pollution control dam, the water may be controlled by evaporation or conveyed directly to the plant for re-use. This is achieved in the model by passing the water from the pollution control dam to the central pollution control dam. If the dam is not connected to the mine water circuits, the dam will spill directly to the river.

Undisturbed Area: This is the portion of the pit reserve area which is not yet mined and is still in a natural state. The surface runoff from the area runs to the river. In most cases high wall cut off berms or diversion trenches area used to direct the runoff from this area away from the mining activities towards the river.

Disturbed Area: The disturbed area is the area of the reserves that have already been mined. This includes the spoil heaps immediately behind the workings as well as the various stages of the pit rehabilitation. The disturbed area has been divided into two parts:

The disturbed area whose recharge goes to spoils storage and whose runoff goes back to the river system; and
A fraction of the disturbed area which contributes runoff and recharge directly to the workings. This is called the disturbed area to the workings in Figure 13.2.

Once the mining of the opencast pit has been completed, the workings could be rehabilitated and the distributed area made free draining with the runoff going to the streams and rivers. In some cases however the final void is not rehabilitated and is used to control the level of the water in the spoils body by evaporation. To cater for this case in the model, the spoils store can be given an evaporation area. This area need not be the same as the area of the workings. In addition, the final void evaporation area may receive surface runoff. To allow for this, the disturbed area to workings can contribute surface runoff to the pit after closure.

Inspoils Dam: The storage volume in the spoils created behind the workings is represented as a dam. The recharge through the disturbed area fills the dam up while the mine is operational. Once the mining is complete, the surface runoff from a portion of the disturbed area could run into the pit if the pit is not completely free draining and a final void is left. In this case the disturbed area to workings is used to represent that area whose runoff will go to the final void after closure.

13.2.3 Water quantity algorithms

There are a number of parameters that will be used in the model that vary in time. The values at various dates over the life of the mine will be specified in the input to the model. The year in which these parameters change will be input into the model. The parameter values being interpolated on a monthly basis between these values.

The algorithms and variables used in the model are described below:

Disturbed Area
The runoff and recharge for a particular month from the disturbed area, whose recharge enters the spoils storage, is given by;

Surface Runoff (directed through river channel out of mine model)

$$QDA = \frac{QVELD}{1000} * ADA * QFDA \quad \text{………………………………………………………..(13.1)}$$

Recharge

$$RDA = \frac{RAOM}{1000} * ADA * RFDA \quad \text{……………………………………………………………..}(13.2)$$

Where:

- QDA is the runoff volume from the disturbed area in million m^3 /month;
- QVELD(mm) is the unit runoff from the naturalized catchment surface (from desegregation of QP);
- ADA (km^2) is the disturbed area for the particular month being computed. This is time varying input parameter. The value for the computation month is interpolated from annual input values;
- QFDA is a runoff factor to adjust the natural runoff for the change in surface conditions of the disturbed area (constant over simulation period);
- RDA is the recharge volume through the disturbed area in million m^3/month;
- RAIN (mm) is the rainfall for the month and
- RFDA is the fraction of the rainfall that will infiltrate below the upper soil layers to recharge the spoils storage. This factor will vary from month to month depending on the season. A value is input for each month. These values remaining constant over the simulation period.

13.2.3.1 Disturbed area to workings

The runoff and recharge that will enter the workings during the operation of the opencast pit is given by:

Surface Runoff

$$QDAW = \frac{QVELD}{1000} * ADAW * QFDAW \quad \text{……………………………..……………..}(13.3)$$

(*Flow through the river channel out of mine model*)

Re charge

$$RDAW = \frac{RAIN}{1000} * ADAW * RFDAW \quad \text{……………………………………………………………..}(13.4)$$

Where

- QDAW is the runoff from the disturbed area in million m^3 / month;
- ADAW is the area (km^2) of the disturbed area whose runoff and recharge enters the workings during the pit operation. After closure the runoff from the area will enter the final void if it is not rehabilitated. ADAW is a time varying input parameter whose values are interpolated from annual input values;

- QFDAW is a runoff factor to adjust the natural runoff for the change in surface conditions of the disturbed area. QFDAW is a constant over the simulation period;
- RDAW is the recharge volume through the disturbed area to the workings in million m^3 / month and
- RFDAW is the fraction of the rainfall that will infiltrate below the upper soil layers to recharge the workings. This factor varies from month to month depending on the season. A value is input for each month. These values remaining constant over the simulation period.

13.2.3.2 Undisturbed Areas

The runoff from the undisturbed area is included in the runoff from the natural portion of the total management unit. This is achieved by correcting the total management unit area for the different area types for each month of the simulation.

13.2.3.3 Water balance for workings

The volume QW (million m^3/month) pumped from the workings is given by:

$$QW = \frac{RAIN}{1000} * AW + QDAW + RDAW \quad \text{..}(13.5)$$

Where AW (km^2) is the area of workings while the pit is operational. Once the pit is closed, the water will not be pumped from the workings and the spoils store will begin to fill up. QW in this case will be zero. This will be achieved in the model by setting AW to zero at a certain date in the input. If AW is zero then QDAW and RDAW will be routed to the spoils store.

13.2.3.4 The volume of water in the spoils storage

The volume of water in the spoils storage at the end of a month will be given by:-

$$If\ AW > \mathbf{0}$$

$$VSD_1 = VSD_O + RDA + AED\left(\frac{RAIN}{1000} - \frac{EVAP}{1000}\right) - QSEEP - QDEC \quad \text{.............................}(13.6)$$

$$If\ AW = \mathbf{0}$$

$$VSD_1 = VSD_0 + RDA + AED\left(\frac{RAIN}{1000} - \frac{EVAP}{1000}\right) - QSEEP - QDEC + RDAW + QDAW \quad (13.7)$$

To determine the seeps, decants and volumes, the following procedure is followed:

$$VSDS \leq VSD_o \leq VSDD \text{ then}$$

$$QSEEP = (QSEEPMAX)\left[\frac{VSD_0 - VSDS}{VSDD\ VSDS}\right] \square^{-exp} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13.8)$$

$$QDEC = \mathbf{0}$$

$$VSD_0 > VSDD \text{ then}$$

$$QDEC = VSD_0 - VSDD \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13.9)$$

$$QSEEP = QSEEPMAX \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13.10)$$

Where

- VSD is the volume of water in the inspoils store in million m^3. The subscripts 0 and 1 represent the start and end of month respectively;
- AED is the evaporation area (km^2) that can be assigned to the inspoils store. This is used to simulate the closure plans employed by some lines to evaporate the pit water make from the opencast pit final voids. The parameters AED varies in time and values will be specified in the input;
- QSEEP (million m^3/month) is the water that can seep from an opencast pit through the weathered zone in the soil profile;
- VSDS (million m^3) is the storage volume in the spoils store at which seepage through the weathered zone can start. This is a time varying input parameter;
- VSDD (million m^3) is the storage volume in the spoils store at which decant occurs. This is a time varying input parameter;
- Exp1 is an exponent;
- QSEEPMAX is the max seepage rate (million m^3/month) that can occur from the spoils store when $VSD_0 \geq$ VSDD. The value for this variable input to the program;
- QDEC is the volume of water that decants from the spoils store in million m^3/month when $VSD_0 >$ VSDD and
- EVAP is the monthly evaporation depth (mm/month).

13.2.3.5 Water Balance PCD

$$VPC_1 = VPC_0 + AFPC\left[\frac{RAIN}{1000} - \frac{EVAP}{1000}\right] + QSEEP + QDEC + QW \quad \ldots\ldots\ldots\ldots(13.11)$$

If

$$VPC_1 > VFPC \text{ then}$$

$$QSPILL = VPC_1 - VFPC \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13.12)$$

If

$$VPC_1 = VFPC$$

QSPILL goes to central pollution control dam

If

$$VFPC > \mathbf{0}$$

QSPILL goes to the river

Where

- VPC is the volume of water in the pollution control dam. The subscript 0 and 1 refers to the volume at the start and end of the month respectively;
- AFPC is the surface area of the pollution control dam (km^2);
- VFPC is the full storage capacity of the pollution control dam (million m^3) and
- QSPILL is the overflow from the pollution control dam (million m^3/month).

13.3 Underground Sub-Module

13.3.1 Water Quantity Algorithms

The underground sub-module consists of an underground storage dam, two undermined surface areas immediately above the storage dam and an upstream catchment whose runoff passes over the high extraction undermined area. One of the areas represents the area undermined by high extraction mining and the other the area undermined by bord and pillar mining. Both high extracting and bord and pillar mining techniques can therefore be accommodated in the modelling framework.

The flow paths of the sub-module are shown in Figure 13.3. There is a recharge to the underground storage tank which is a function of the recharge through the catchment surface, groundwater and a fraction of the recharge through the catchment surface, groundwater and fraction of the runoff from the upstream catchment. During operation. water can be pumped from underground or excess water on the mine complex can be pumped underground. This pathway is represented as a constant flow to or from the central pollution control dam.

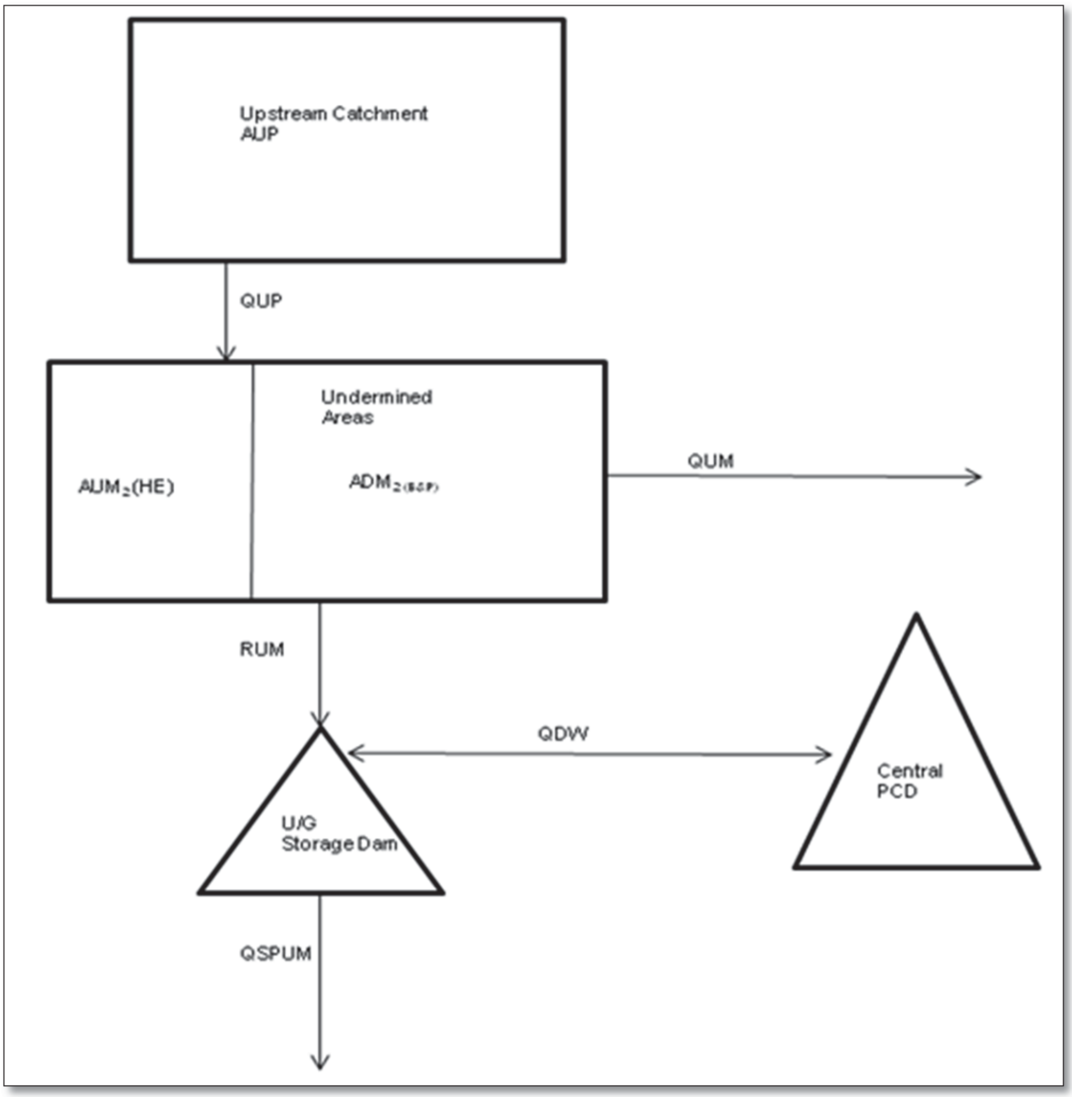


Figure 13.3: Flow Path for Underground Sub-module

The surface runoff from the upstream catchment is given by:

$$QUP = AUP\,\frac{QPER}{\mathbf{1000}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13.13)$$

Where:

- QUP is the surface runoff volume from the upstream catchment in million m^3/month;
- AUP is the area (km^2) of the catchment upstream of the undermined catchment. This variable will be kept constant over the simulation period and
- QPER is the unit runoff from the associated salt washoff model (mm).

The recharge to the underground mine RUM is then given by:

$$RUM = RFUP \times QUP + \frac{RAIN}{1000}\ (AUM1 \times RFUM1 + AUM2 \times RFUM2)\ \ldots.\ldots (13.14)$$

Where:

- $RFUM_1$ and $RFUM_2$ are monthly recharge factors, which are input to the model, A value is input for each month of the year. These values will remain constant over the simulation period. The subscript 1 and 2 refers to the bord and pillar and high extraction mining respectively;
- RFUP is a recharge factor, which is input to the model. This is the fraction of the upstream runoff volume, which will recharge the underground storage dam. A value is input for each month of the year. The values remain constant over the simulation period and
- AUM_1 is the undermined catchment area (km^2) for bord and pillar mining and AUM_2 is the undermined catchment area (km^2) for high extraction mining . This value will vary in time. A monthly value will be interpolated form annual input values.

The surface runoff from the undermined area which returns to the river system is given by:

$$QUM2\ = \frac{QVELD}{1000}\ AUM2 \times QFUM2\ (1 - \ RFUP)\ QUP\ (High\ extraction\ section)\ \ldots.(13.15)$$

$$QUM_1 = \frac{QVELD}{1000} AUM_{1\,(Bord\ and\ pillar\ section)}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(13.16)$$

Where:

- QUM is surface runoff volume from the undermined areas in million m^3/month;
- QFUM is a dimensionless runoff factor, which is constant over the simulation period and
- The surface runoff from the area undermined by bord and pillar mining is assumed to be part of the natural runoff.

The water balance for the underground storage modelled though a network storage dam, reservoir sub-model.

13.3.2 Water quality algorithms

The water quality of the stream of water from the underground mines will be determined in the same way as for the seeps and decants from the opencast pits. The stochastic generator will be used bases on the mean and standard deviation determined from the measure water quality results.

The surface washoff from the Bord and Pillar undermined area and the upstream area will be modelled using the surface washoff for the natural areas.

13.4 Discard/Slurry Ponds

13.4.1 Water quantity algorithms

The slurry ponds and discard dumps generally have a decant system to drain the rainwater and the supernatant from the tops of the dumps to a return water dam. In addition to the decant, seepage and surface runoff from the dump is often collected in a system of drains and trenches and conveyed to the return water dam. In developing the dump model, the assumption has been made that a fraction of the slurry water leaving the plant is returned to the plant from the return water dam. Rather than model the complete slurry water circuit, the water demand at the plant is reduced to allow the recycle of slurry water.

The modelling of the discard dump is then reduced to the prediction of spills from the return water dam due to the runoff from the dump surface, seepage from the dump and rainfall directly on the dam surface. The flow pathways are shown in Figure 13.4. These consist of a surface runoff and a seepage flow. The seepage flow can be split with a fraction going to the pollution control dam and a fraction directly to the river.

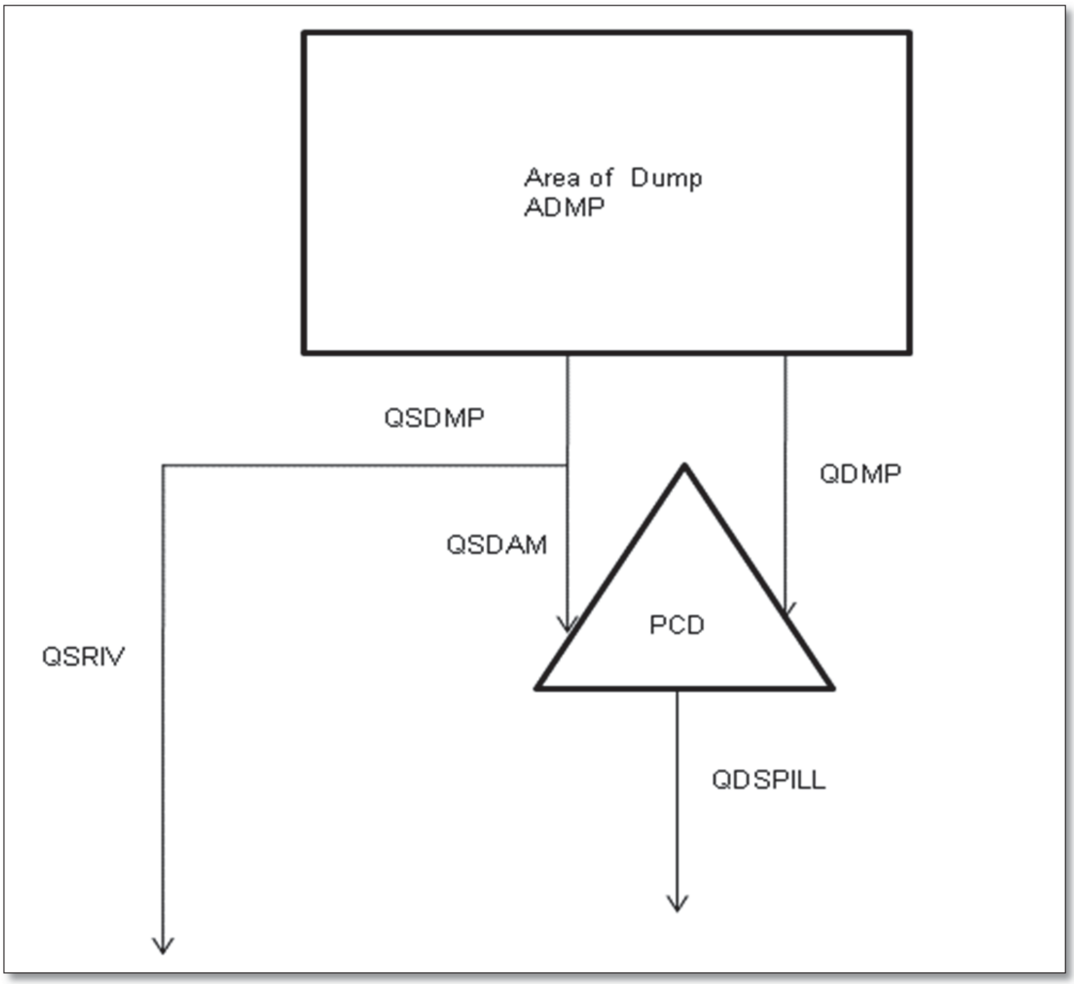


Figure 13.4: Flow Path for Discard Dump

The surface runoff volume QDMP (million m³/month) is given by:

$$QDMP = ADMP \frac{RAIN}{1000} QFDMP \qquad \ldots\ldots(13.17)$$

Where:
ADMP (km^2) is the surface area of the dump. This is a time varying input parameter. The value for a month is interpolated from annual input values.

QFDMP is a runoff factor for the dump. This factor is constant over the simulation period.
The seep volume QSDMP (million m^3/month) is given by:

$$QSDMP = ADMP \frac{RAIN}{1000} RFDMP \qquad \ldots\ldots(13.18)$$

Where:

RFDMP is the dimensionless monthly recharge factor, which is constant over the simulation period.

The fraction FDMP is used to split QSDMP between the dam and the seep directly to the river. The results in:

$$QSRIV = QSDMP * FDMP \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13.19)$$

$$QSDAM = QSDMP - QSRIV \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13.20)$$

Where:
QSRIV is the volume of water (million m^3) that seeps to the river;
QSDAM is the volume of water (million m^3) that flows to the PCD.

$$VDD_1 = VDD_0 + QSDAM + QDMP + \frac{ADD(RAIN - EVAP)}{1000} \quad \ldots\ldots\ldots\ldots\ldots (13.21)$$

The water balance for the PCD is given by

Where:
VDD is the volume of water in the PCD for the dump and
ADD is the surface area of the dump PCD in km^2.
If VDD, is greater than the dump PCD full capacity VFDD then:

$$QDSPILL = VDD_1 - VFDD \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13.22)$$

QDSPILL is routed to the central PCD.

13.4.2 Water quality algorithms

A sulphate concentration is required for QSRIV and QDSPILL. Water quality data has been made available of the water in the return water or PCD at the dumps. This information will be used to obtain a mean and a standard deviation to stochastically generate a sulphate concentration CDSPILL for each month. The sulphate concentration CSRIV of the seepage to the river QSRIV will be obtained by means of calibrating the low flow sulphate concentrations in the rivers.

13.5 Central Pollution Control Dam

The central PCD is a combination of the PCD's on the mine complex. The central PCD receives water from a number of sources, which are shown in Figure 13.1. The central PCD will be assigned a penalty structure, which will allow for the simulation of controlled release to the river system and the pumping of water underground. The quantity and quality balances are simulated by the reservoir sub-model.

13.6 Beneficiation Plant

13.6.1 Water quantity algorithm

The runoff from the plant area QPRO is calculated y:

$$QPRO = \frac{RAIN}{1000} APNT * QFPNT \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13.23)$$

Where:
APNT (km^2) is the plant area whose runoff reaches the central PCD. This is a time varying parameter interpolated form annual input; and
QFPNT is a dimensionless runoff factor used to adjust QPRO for the fraction of APNT that is impervious and directly connected to the central PCD.

The variables used in the model are described in Table 13.1 below.

Table 13.1: Variables used in the mining module

Parameter/Variable	Description
INPUT PARAMETER	
ADA	Surface area of disturbed area whose recharge goes to the spoils store (m^2). Interpolated for each month form annual input values
ADAW	Surface area of disturbed area to workings (m^2). Interpolated for each month from annual input figures.
AED	Evaporation area of inspoils store (km^2). Used to simulate the evaporation form a final void if left after closure. A time varying variable
AFPC	Surface are of opencast pollution control dam at full storage (km^2)
ARES	Surface area of coal reserves being mined (m^2).
AW	Surface area of workings (km^2). Constant over the life of the mine
EVAP	Monthly evaporation depth (mm/month)
EXP1	
QFDA	Runoff factor for disturbed area (dimensionless) for opencast pit. Constant over simulation period.
QFDAW	Runoff factor for disturbed area to workings (dimensionless).
	This factor is constant over the simulation period.
QNAT	Naturalised total runoff from catchment (mm/month)
QSEEPMAX	The maximum seepage rate (million m^3/month) that can occur through the soil profile from opencast pit in spoils store.
QVELD	Naturalised unit surface runoff (mm/month)
RAIN	Monthly rainfall depth (mm/month)
RFDA.	Recharge factor for disturbed area (dimensionless). A value is input for each month of the year. These values are constant over the simulation period.

Parameter/Variable	Description
RFDAW	Recharge factor for disturbed area to workings (dimensionless). A value is input for each month of the year. These values are constant over the simulation period.
VFPC	Capacity of pollution control dam (million m^3) for opencast pit.
VSDD	
VSDS	Storage volume in the spoils store at which seepage though the weathered zone can start. This is a time varying input parameter.
CALCULATED VARIABLES	
APC	Surface area of pollution control dam (km^2)
AUD	Surface area of undisturbed area (km^2)
QDA	Runoff to river from disturbed area (million m^3/month)
QDEC	Volume of water that decants from the spoils store in million m^3/month.
QDAW	Runoff to workings from disturbed area (million m^3/month)
QSEEP	The water volume (million m^3/month) that can seep from an opencast pit through the weathered zone of the soil profile.
QUDA	Runoff to workings from disturbed area (million m^3/month)
QW	Volume of water (million m^3/month) pumped form workings to the PCD.
RDA	Recharge from disturbed area to inspoils store (million m^3.month)
RDAW	Recharge from disturbed area to working (million m^3/month)
VPC	Volume of water stored in the pollution control dam (million m^3) for opencast pit.
VSD	Volume of water in spoils dam (million m^3)

13.7 Data File Format

13.7.1 Mine Sub-Model

The reader should refer to the report “Water Quality Modelling, Volume A: Water Quality Calibration Model” number PC000/00/7086 of the Department of Water Affairs and Forestry for the basic description of the network definition, system configuration and other files. The formats of the input files of the following sub-models are given in detail in the aforementioned report:

- reservoir sub-model;
- salt washoff sub-model;
- irrigation block sub-model;
- junction node sub-model;
- channel/river reach sub-model; and
- demand centre sub-model.

Input data are required for the developed Mine Model and the naming convention and format of the data file is described below.

The file name for the Mine Sub-model uses the same naming convention as described in the above-mentioned report and a typical name for a mine sub-model file would be “mimm300.dat “. Where “mi” refers to the system identification code, “mm” indicates that the specific file contains data for a Mine Sub-model and “300” refers to a unique number assigned to the particular sub-model.

14 DAILY TIME STEP MODEL

14.1 Introduction

A Pitman daily time step model has been in existence since 1976 but remained in its original DOS form until a couple of years ago when it was decided to transform it into a similar model to the WRSM/Pitman monthly time step. A report entitled “A Mathematical Model for Generating Daily River Flows from Meteorological Data in South Africa” (Pitman W.V, 1976) was written by Dr Bill Pitman in March 1976 and contains a detailed methodology and all the tests carried out on a number of catchments. The WRSM/Pitman User Guide also explains how the user should prepare data, analyse a system and obtain results in the form of hydrographs and time series daily streamflow.

14.2 Methodology

The full methodology has not been repeated here but has rather been summarised with insight provided as to how it was incorporated into a model similar to the WRSM/Pitman monthly time step. A daily time step is often necessary to analyse streamflow from an ecological point of view and also in operating dams, designing river diversion works, coffer dams and off-channel dams.

The WRSM/Pitman daily time step model was designed to generate daily flows using as input daily and monthly rainfall and average monthly potential evaporation. The structure is similar to that of the monthly time step with similar calibration parameters. Figure 14.1 shows a flowchart representation of the model. Assumed soil moisture conditions is determined from initial catchment discharge, precipitation is stored as interception and as soil moisture and this is subject to evaporation and transpiration. The quantity of precipitation that is not absorbed by the soil is the source of surface runoff. A portion of the precipitation held as soil moisture percolates into groundwater before entering the river system. The various components are suitably lagged and the total runoff at the catchment outlet is computed on a mass balance basis.

The model has been designed to balance the catchment’s water budget and hence to determine the runoff using different time steps. For days during which there is no rain, a one-day time step is used. When a rain-day is encountered, the duration of the fall is estimated and the rainfall total is distributed as hourly amounts in order that the water budget may be computed at one-hour time intervals. After cessation of the storm a single time step of n hours is employed, where n = 24 – duration of the rainfall. It is thus evident that the onset of rain is assumed to coincide with the beginning of the day. Duration of rainfall is assumed via the following linear equation and is then rounded to the nearest whole number of hours.

$$\text{Duration (h)} \qquad = \text{AA} + \text{BB x rainfall (mm)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14.1)$$

The suggested default values for AA and BB are 0.964 and 0.13736 respectively. The temporal distribution of rainfall is assumed to follow an S-curve, the details of which are given in the reference (Pitman, 1976).

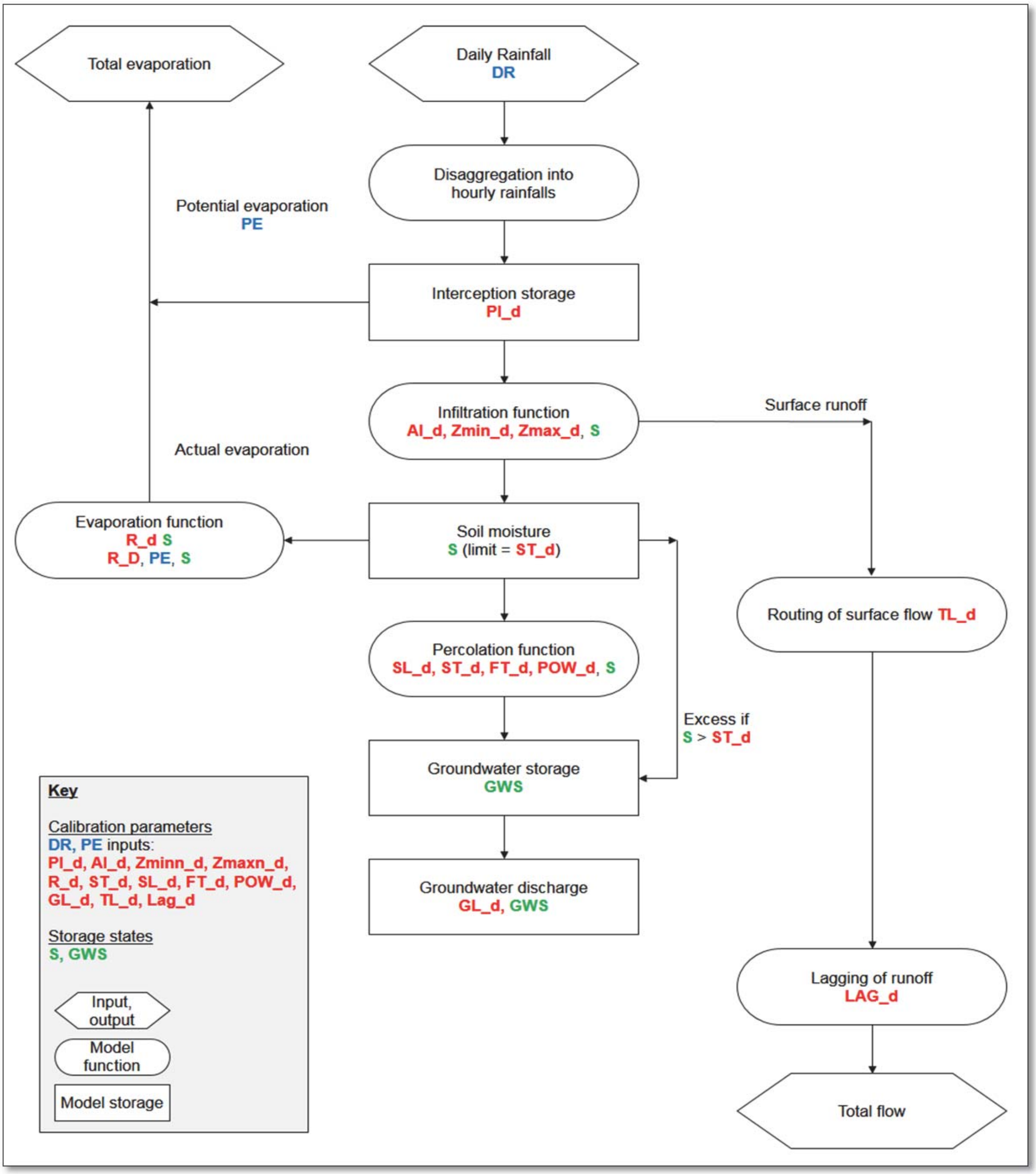


Figure 14.1: WRSM/Pitman Daily Model Flowchart

Regarding interception, vegetation and soil surfaces may be initially dry before a fall of rain and a small amount of moisture is needed to wet these surfaces before runoff and infiltration can occur. This function is represented by assuming an interception storage (**PI_d**) which must be filled before precipitation is available for infiltration and runoff. Moisture from interception storage is removed at the potential evapotranspiration rate until all moisture is exhausted.

Regarding surface runoff, it is taken to be derived from two sources namely:

Runoff from impervious areas and
Runoff resulting from rainfall that has not infiltrated into the soil.

The first component is computed by multiplying the rainfall available for infiltration and runoff by the area of catchment that is impervious. The impervious area (**AI_d**) is the proportion of the catchment that contributes directly to surface runoff. Impervious areas not directly connected to water courses must flow over pervious areas before reaching a stream channel. Isolated impervious areas are therefore not included in parameter **AI_d**.

For the second component, it was recognised that infiltration would be highly unlikely to be uniform throughout the catchment. The spatial distribution of infiltration rate is no doubt strongly influenced by physical features such as geology, soil type, vegetation and many others too numerous to mention. In most natural catchments these factors would result in a considerable spatial variation in infiltration rate. It was felt that a reasonable approximation could be reached by assuming a triangular frequency distribution of infiltration rate, thus reducing to a manageable number the parameters relating to this phenomenon. As in the case of the monthly model a symmetrical triangular frequency distribution was adopted using **Zminn_d** and **Zmaxn_d**. However, the daily model allows for the infiltration capacity to vary with the soil moisture status, unlike the monthly model. Further details and mathematical equations are available in the reference (Pitman, 1976).

Regarding infiltration, the quantity of water entering storage as soil moisture is simply the residual precipitation after interception and surface runoff have been subtracted.

Regarding evaporation, to achieve maximum simplification of computations and also to keep the number of parameters manageable, the evaporation- soil moisture relationship was assumed to lie anywhere between limits shown by graphs of catchment evaporation against soil moisture using the parameter **R-d**. These algorithms are identical to those used in the monthly model. Further details, graphs and mathematical equations are available in the reference (Pitman, 1976).

A regards percolation of soil moisture to groundwater storage, this is shown by a graph of percolation against soil moisture which has the form of a power curve that is identical to that used in the monthly model and uses model parameters **SL_d**, **ST_d**, **FT_d** and **POW_d** and takes the following form, where S is the current soil moisture status.

$$\text{Percolation} = \text{FT\_d}\left((\text{S} - \text{SL\_d})/(\text{ST\_d} - \text{SL\_d})\right)^{\text{POW\_d}} \tag{14.2}$$

Regarding groundwater discharge, numerous trials revealed that the adoption of a single recession constant was not satisfactory and that a variable recession constant, related to the groundwater storage state, led to more accurate results. An equation of the following form was adopted to determine the groundwater flow GWF:

$$\text{GWF} = (1/\text{GL\_d}) \text{ x } \text{GWS1.5}/\sqrt{}\text{ST\_d} \tag{14.3}$$

Where **GL-d** = model parameter for groundwater lag and **ST_d** is the model parameter for soil moisture storage capacity.

Further details, graphs and mathematical equations are available in the reference (Pitman, 1976).

Finally, regarding the time delay and attenuation of runoff, since this model is a lumped model, i.e. the response of the whole catchment is characterised by the processes taking place at a representative location, the components of model runoff may have to be lagged to indicate the runoff at the catchment outlet. Furthermore, surface runoff is subject to attenuation as it moves across the land surface and then through the channel system. Runoff lagging is achieved with the aid of the parameter **LAG_d**, which must be an integral number of days if not zero. The total runoff computed for day n is then assumed to appear at the catchment outlet at day (n+ **LAG_d**).

Attenuation of surface runoff is accomplished using the Muskingum equation with the parameter “X” equal to zero as follows:

$$\text{O2} = \text{O1} + \text{C1}(\text{I1} - \text{O1}) + \text{C2}(\text{I2} - \text{I1}) \tag{14.4}$$

Where

$$\text{C1} = 1/(\text{TL\_d} + 0.5) \text{ and } \text{C2} = \text{C1}/2 \tag{14.5}$$

Further details and mathematical equations are available in the reference (Pitman, 1976).
The above methodology was brought into the WRSM/Pitman model daily time step version which had some new input screens and additional daily input and parameters. There is a new screen for daily calibration parameters. The WRSM/Pitman User Guide explains how the daily time step version works, describes the conversion utilities within WRSM200/Pitman for formatting for daily rainfall and daily observed streamflow and gives a guide on the

additional parameters required. Table 14.1 shows the relationship/conversion between the monthly and daily calibration parameters.

There are two distinct modes for analysing daily flows as follows:

- daily naturalised flow. Here the user is only interested in the naturalised flow, i.e. without any man-made influences such as dams, irrigation schemes, industry and urban requirements, etc. and
- daily streamflow that would occur in a system with various land uses where the user may want to compare simulated streamflow against daily observed streamflow.

Full details of what is required to analyse systems for these two modes are given in the WRSM/Pitman User Guide.

Table 14.1: Conversion from monthly to daily calibration parameters

Calibration Parameter	Monthly	Daily	Suggested Rule
POW	2	2	No difference
SL	0	0	Usually = 0
ST	160	160	No difference
FT	20	0.3	FT (Daily) = 0.024 of monthly (=0.48)
AI	variable	0	
Zmin	999	0	None (range 0-3 for daily)
Zmax	999	15	None (range 6-15 for daily)
PI	1.5	1.5	
TL	0.25	5	TL (daily)= 1 + 0.00025 × Area (km^2) × TL (monthly model – months) / 0.25 =
Lag	Not used	0	
GL		10	GL (daily model – days) = 25 × GL (monthly model – months) (If Pitman method used otherwise default value)
R	0.5	0.5	No difference

Note that the daily model parameters have the suffix "_d" to distinguish them from those used in the monthly time-step model. Parameters Zmin and Zmax also have an added "n" to indicate nominal values, as the actual values vary according to soil moisture status.

The following schematic in Figure 14.2 shows in simplified form the methodology for using a daily time step.

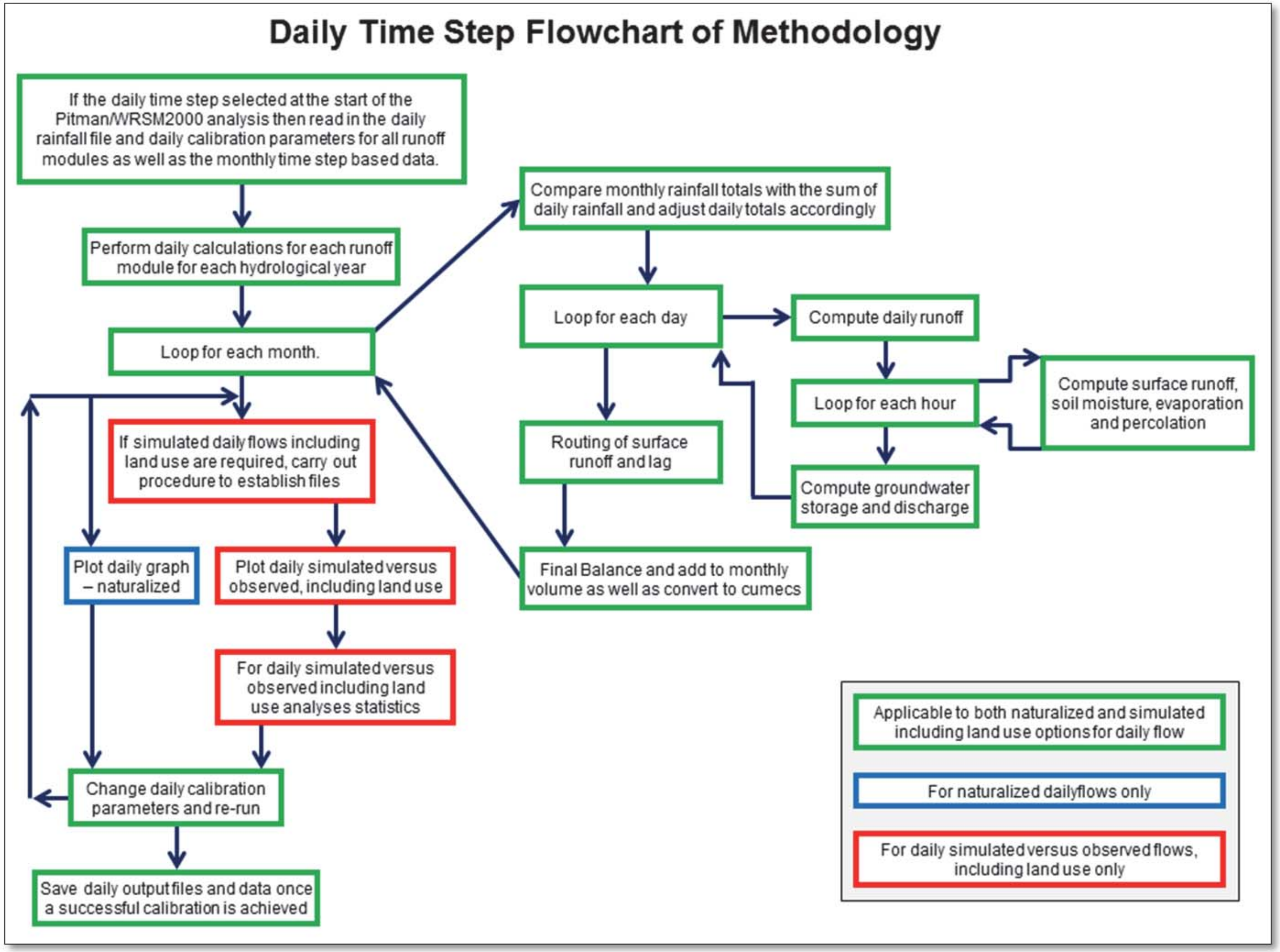


Figure 14.2: Flowchart of daily time step process

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