Practical experience with using the WQT irrigation block in the WRSM2000

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Abstract

The WQT salinity modelling system was developed in the late 1980s for the Department of Water Affairs and Forestry and has been used successfully throughout South Africa for Total Dissolved Solids (TDS) modelling. The model contains an irrigation block sub-model which simulates irrigation of different crops and the resulting return flows by taking account of rainfall, evapo-transpiration and soil characteristics (indirectly). This irrigation sub-model has recently been improved, incorporated into the WRSM2000 model and used in studies. This paper will describe the basic principles of the sub-module; the improvements made to it and illustrate the application of the model, based on practical experience.

Keywords: *Irrigation requirement modelling, hydrology,*

1. Introduction

The WQT model is a simulation software system developed in the mid 1980's to assist in the evaluation of salinity related management measures, initially for the Vaal River system, and later applied to other water resource systems in South Africa. The model makes use of discreet network elements to simulate the effects of salts generated from catchments (washoff), salt balance in reservoirs, demand centres representing urban developments, irrigation areas and processes influencing the water and salt balance in river reaches (Allan and Herold, 1988). The irrigation sub-model accounts for the continuity of salts mass and allows accumulation and flushing of salts from irrigation areas on a monthly time-step. The irrigation block sub-model takes into account several aspects of modelling theoretical irrigation demand, including changes in a theoretical sub-surface storage and associated return flow estimates as well as canal transfer losses.

The functionality of the WQT irrigation block sub-module was identified as the appropriate simulation method for scenario planning for incorporation into the hydrological and system analysis models used by the Department of Water Affairs and Forestry (DWAF) of South Africa for water resources planning assessments (De Jager and Van Rooyen, 2005). The WQT irrigation block (or sub-model) had functionality not made provision for in the current hydrological models which could improve model calibration and scenario management capabilities.

The hydrological model in which the irrigation block sub-model was incorporated is the Water Resources Simulation Model 2000 (WRSM2000), the standard river-runoff model used by DWAF for large scale water resource analyses. The WRSM2000 is a hydrological simulation model which is used to simulate the movement of water through an interlinked system of catchments, river reaches, reservoirs and irrigation areas. The model can simulate wetlands and more recently was updated to also accommodate, mines, urban demand centres as well as estimating the impact of groundwater abstraction on surface water (Pitman et. al., 2006). The WRSM2000 is a monthly hydrological rainfall-runoff simulation model which is used to determine long-term naturalize flow records, which serves as input into risk based system yield accounting models.

This article describes the basic capabilities, improvements done and results from a typical application of this irrigation sub-module.

2. Basic principles

The basic concepts of the irrigation block as implemented in the WRSM2000 are discussed in the following sections, making use of Figure 1 below (De Jager and Van Rooyen, 2005, after Allan and Herold, 1988).

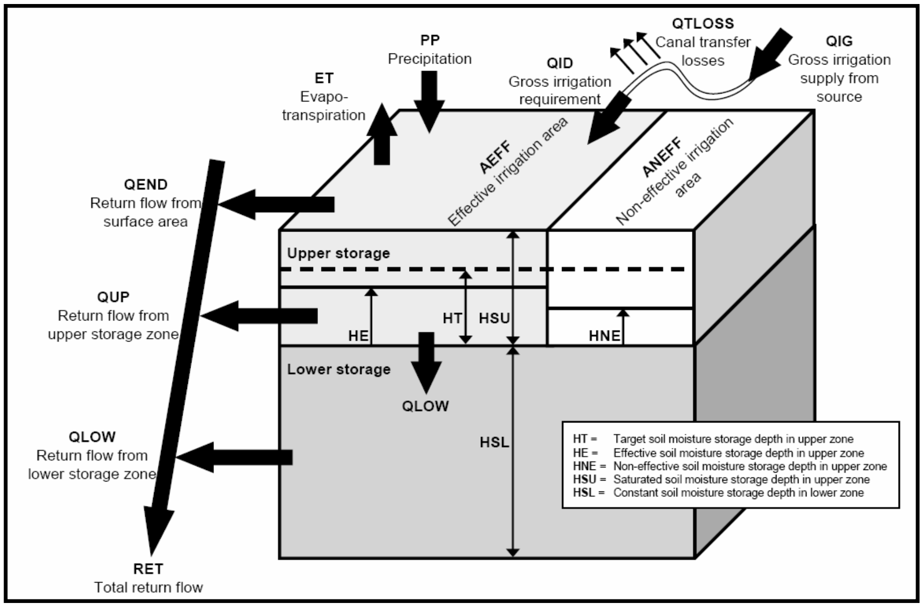

Figure 1: Conceptual diagram of the WQT irrigation block sub-model

2.1 Irrigation requirements

The irrigation sub-model calculates a monthly unit irrigation requirement as follows:

$$\mathrm{DIN} = \sum_{i=1}^{\#\mathrm{crops}} \mathrm{CPF}_i * (\mathrm{PE}_m * \mathrm{CF}_{im} - \mathrm{ER}_m)/100 \qquad (1)$$

Where:

DIN = monthly unit irrigation requirement, where DIN >= 0 [mm/month]
CPF_i = percentage of total irrigated area cultivated using crop i [%]
PE_m = potential evaporation for month m [mm/month]
CF_{im} = crop i demand factor for month m [factor]
ER_m = monthly effective rainfall [mm/month]

2.2 Gross monthly irrigation supply

In order to allow for leaching requirements, application losses and canal transfer losses in transporting water from the water source to the irrigation area, the gross irrigation supply is calculated in the following manner:

$$\mathrm{QIG} = (\mathrm{DIN} * \mathrm{AEFF} * 10^{-3}) * 100/\mathrm{EFI} * (1 - \mathrm{TLPQ})^{-1} \qquad (2)$$

Where:

QIG = gross monthly irrigation supply from the raw water source (including losses) [million m^3/month]
DIN = monthly unit irrigation requirement (Eq 1) [mm/month]
AEFF = effective irrigation area [km^2]
EFI = irrigation water use efficiency [%]
TLPQ = proportion of canal flow lost in transport [factor]

2.3 Effective and non-effective areas

The irrigation sub-model calculates for each month an effective and non-effective irrigation area based on whether the required irrigation supply volume (Equation 2) is greater than the volume available from the raw water source. The effective irrigation area is calculated by means of the following equation:

$$\mathrm{AEFF} = \mathrm{AREAT} * \mathrm{QAVAIL} / \mathrm{QIG} \qquad (3)$$

Where:

AEFF = effective irrigation area [km^2]
AREAT = adjusted irrigation area to allow for an annual maximum allocation limit [km^2]
QAVAIL = available water from raw water source [million m^3/month]
QIG = gross monthly irrigation supply from the raw water source (including losses) [million m^3/month]

The non-effective irrigation area is calculated as the difference between the gross irrigation area and the calculated effective irrigation area. The concept of effective and non-effective irrigation areas is artificial, designed to account for the situation where irrigation volumes are decreased to account for insufficient water availability and it does not necessarily imply that the actual irrigation area is reduced. The annual maximum allocation limit allows for the simulation of planned curtailments, where irrigators are informed of reduction of their allocation prior to the planning season.

2.4 Monthly return flow volume

The average soil moisture storage depth for the effective area (HE) as well as the non-effective (HNE) is calculated by the irrigation sub-model using a basic monthly water balance of all water being applied and removed from the irrigation area over the month, depending on certain conditions. Given the average soil moisture depth, a unit return flow seepage is calculated for the effective area (and similarly for the non effective area) as in the equation below:

$$\mathrm{RE} = \mathrm{QC} + \mathrm{HE} * \mathrm{RF} \qquad (4)$$

Where:

RE = unit return flow seepage from effective irrigation area [mm/month]
QC = unit runoff from pervious zone of catchment [mm/month]
HE = average soil moisture storage depth in month for effective irrigation area [mm/month]
RF = return flow factor [factor]

The monthly return flow volume from both the effective and the non-effective irrigation areas is added to obtain the total irrigation return flow volume, as shown in the equation below:

$$\mathrm{RET} = (\mathrm{RE} * \mathrm{AEFF} + \mathrm{RNE} * \mathrm{ANEFF}) * 10^{-3} + \mathrm{RC} \qquad (5)$$

Where:

RET = total monthly irrigation return flow volume [million m^3/month]
RE = unit return flow seepage from effective irrigation area [mm/month]
AEFF = effective irrigation area [km^2]
RNE = unit return flow seepage from non-effective irrigation area [mm/month]
ANEF = non-effective irrigation area [km^2]
RC = return flow seepage from canal losses [million m^3/month]

Finally, the total return flow from the irrigation area is assumed to come from three different paths, an upper and lower zone as well as from the surface area. The adjustment of fractions of total return flow from the different zones is mostly used in the WQT model to correct salt balances. Only the total return flow is of concern for the WRSM2000 implementation to provide the correct estimate of total return from the irrigation sub-module.

3. Improvements

Some recent improvements to the WRSM2000 irrigation module was done based on the recommended use of the SAPWAT crop requirements database in studies to assess water availability in stressed catchments undertaken by DWAF (De Jager and Van Rooyen, 2005). In addition the Mokolo landuse validation studies (Schoeman and Joubert, 2007), that provides input into the water availability assessment study, recommended the addition of a drought reduction factor to the theoretical irrigation demand calculation of the WRSM2000. The sections below describe these improvements.

3.1 SAPWAT crop requirements

SAPWAT is an irrigation crop requirements database and simulation software developed by the Water Research Commission (WRC) of South Africa to determine the water requirements of crops for different areas in South Africa, taking into account irrigation practises and climatic conditions. SAPWAT can produce the monthly evapo-transpiration for different crops associated with an irrigation area under consideration. The monthly crop evapo-transpiration data play an important role in the modelling irrigation water requirements and return flows

SAPWAT estimates monthly crop evapo-transpiration based on the Penman-Monteith (short grass) reference evaporation, and is calculated as shown below (Van Heerden and Crosby, 2002):

$$ET_{crop} = ET_o * k_c \qquad (5)$$

Where:

ET_{crop} = monthly crop evapo-transpiration [mm/month]
ET_o = monthly Penman-Monteith (short-grass) reference evaporation [mm/month]
k_c = monthly SAPWAT crop factor [factor]

Regionalised default values for the above parameters are available from the SAPWAT database, for a variety of crop types and plant dates. However, specific crop requirements can be extracted from the database based on validated landuse information.

To accommodate the use of SAPWAT crop evapo-transpiration values in the WRSM2000 irrigation sub-module, Equation 1 is changed in the following manner:

$$DIN = \sum_{i=1}^{\#crops} CPF_i * (ET_{(crop)m} - ER_m)/100 \qquad (6)$$

Where:

DIN = monthly unit irrigation requirement, where DIN >= 0 [mm/month]
CPF_i = percentage of total irrigated area cultivated using crop i [%]
$ET_{(crop)m}$ = monthly SAPWAT evapo-transpiration crop requirements [mm/month]
ER_m = monthly effective rainfall [mm/month]

3.2 SAPWAT effective rainfall

The original irrigation block applied determined effective rainfall in the following manner as input to Equation 1:

$$ER_m = ERF_m * Rain_m \qquad (7)$$

Where:

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

SAPWAT makes use of a formula to calculate the effective rainfall, which takes cognisance of the available water retaining-capacity of the soil in that it accounts for the monthly evapo-transpiration (Schoeman and Joubert, 2007). This formula was also incorporated into the irrigation sub-module. In the SAPWAT the maximum monthly evapo-transpiration considered is limited to 75 mm, and use in calculating the effective rainfall in the following manner:

$$ER_m = ET_{(crop)m}\left(-0.001\frac{(Rain_m)^2}{ET_{(crop)m}} + 0.025\frac{(Rain_m)^2}{(ET_{(crop)m})^2} + 0.0016*(Rain_m) + 0.6\frac{Rain_m}{ET_{(crop)m}}\right) \qquad (8)$$

Where:

ER_m = monthly effective rainfall [mm/month]
(which is smaller or equal to the actual monthly rainfall)
$ET_{(crop)m}$ = monthly representative crop evapo-transpiration (requirement) [mm/month]
(where the maximum value of $ET_{(crop)m}$ = 75mm)
$Rain_m$ = actual monthly rainfall [mm/month]

3.3 Drought reduction factor

The Mokolo River catchment validation of the existing lawful water use study (Schoeman and Joubert, 2007) identified an additional factor that was added as an option to the WRSM2000 irrigation sub-module. The factor simulates on a very elementary level farmers' supplemental irrigation management practices usually relying mostly on river runoff. That is, 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 there is relatively few supply failures and is only aimed at mimicking supplemental irrigation practices. It is therefore implemented as an option in the WRSM2000. The drought reduction factor is defined in the following manner:

$$DF = \mathrm{Max}\left(\frac{\mathrm{Rain}_m}{\mathrm{Rain}_{avg(m)}}, \frac{\mathrm{Rain}_a}{\mathrm{Rain}_{avg(a)}} \right) \qquad (9)$$

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

The drought deduction factor is multiplied with DIN in Equations 1 or 6 to obtain a reduced irrigation requirement for each month.

4. Summary of WRSM2000 irrigation sub-module

In summary the improved WRSM2000 irrigation sub-module simulates a monthly time series of irrigation requirements and return flows, given a combination of the following parameters (Type 2 denotes the SAPWAT improvements made to the original, Type 1, irrigation sub-module):

Table 1: Parameters used within the improved WRSM2000 irrigation module

Parameter	Type 1	Type 2
Monthly evaporation and pan factors	X	
10 Crop types, areas and crop factors	X	
Monthly crop evapo-transpiration requirements		X
12 Monthly effective rainfall factors	X	
Drought reduction factors	X	X
Monthly rainfall record	X	X
Annual historic trend in area under irrigation	X	X
Annual historic trend in return flow	X	X
Annual historic trend in maximum annual allocation	X	X
Annual historic trend in irrigation efficiency	X	X
Canal losses (seepage and return flows)	X	X

5. Data

The improved WRSM2000 irrigation block was used during the hydrological analysis of the Mokolo River Catchment (De Jager et. al., 2007). This study made use of information obtained from the Validation of the existing lawful water use study for the same area. The purpose of the latter study was to determine, verify and validate the actual water use to enable more realistic modelling of water availability in the Mokolo catchment (Schoeman and Joubert, 2007). Therefore as part of this study parameters for estimating irrigation requirements and percentages of return flows had to be calculated, while assumptions for trends in application efficiency and other parameters had to be derived.

The following sections will describe some of the methods used to determine parameters eventually used in the WRSM2000 irrigation block sub-model.

5.1 Processed SAPWAT data

Crop types and irrigation system combinations as well as the position, area and supply source information were gathered through the validation process for the entire of Mokolo catchment. This information was then used to develop for each quaternary a representative month crop requirement, application efficiency and percentage return flow estimate.

The SAPWAT database was use to determine the monthly crop requirement and application efficiency for each crop-irrigation system combination present in a quaternary catchment. All the SAPWAT data was then weighted based on the area of the crop-irrigation system combination versus the total area under irrigation in the quaternary catchment to provide a representative monthly crop distribution and application efficiency for the entire quaternary catchment (Schoeman and Joubert, 2007). An example of how the representative crop requirement and application efficiency was determined for a quaternary catchment is provided in Table 2.

Table 2: Example of determining a representative crop requirement and application efficiency calculation for a quaternary catchment area

Validated quaternary irrigation information				Crop Requirement - SAPWAT							Application Efficiency
				Jan		-	Dec		Annual		
Crop	Season	System	Area (ha)	mm	m^3		mm	m^3	mm	m^3	%
Citrus	Annual	Drip	10.0	116.9	11690.3	-	117.0	11701.5	1021.3	102126.4	95.0
Granadilla	Annual	Drip	2.3	108.9	2504.0	-	109.0	2506.4	950.3	21857.8	95.0
Maize	Summer	Centre Pivot	183.0	102.3	187185.5	-	250.4	458238.7	810.5	1483239.7	90.0
Pastures	Annual	Centre Pivot	63.0	158.9	100137.8	-	147.8	93083.5	1452.5	915049.3	85.0
Watermelon	Summer	Centre Pivot	120.0	20.6	24767.1	-	213.6	256293.7	574.3	689129.8	85.0
Wheat	Winter	Centre Pivot	427.8	0.0	0.0	-	0.0	0.0	671.4	2872173.5	85.0
Total			806.1		326284.7	-		821823.8		6083576.5	
m^3/ha					404.8	-		1019.5		7547.1	
mm/ha					40.5	-		102.0		754.7	86.4

5.2 Other data

Return flow estimates for each quaternary catchment was done based on the catchment representative application efficiency. Due to the high application efficiency in the Mokolo catchment and the absence of canals, the percentage of return flow was estimated as being 50% of the non-efficiency application. No recorded information was available that could be used to calibrate the WRSM2000 simulated return flow, and therefore the expert knowledge from Schoeman et. al. of typical measured values, which correlated with their assumptions, were accepted. The WRSM2000 irrigation module does not simulate a direct fractional relationship with the irrigation demand. The return flow is a function of the average monthly soil moisture depth. Therefore each quaternary catchment's irrigation module had to be "calibrated", using the RF factor from Equation 4, to obtain the same long term annual simulated return flow as percentage of irrigation demand as estimated by the validation study.

Assumptions were also made regarding the historical annual trend in application efficiency, given historical surveys of crops in the area. A linier interpolation from the start of the simulation period (60% in 1920) up to the first survey was assumed. From 1960 the application efficiency was varied per quaternary catchment based on the validation information and the resulting SAPWAT representative data.

Irrigation areas could be determined on a quinary basis for the entire area. An annual growth model was developed for the growth in irrigation area, and was adapted for each quinary to match the actual surveyed information for the quinery. The growth model was developed using benchmark data which were available for the year 1970 (first control instituted in the Mokolo area), 1984/1985 (filed surveys conducted in the area), 1990 (satellite imagery), 1998 (validated registration) and 2004 (satellite imagery). The growth model is based on the following assumptions listed in Table 3:

Table 3: Assumptions for the growth model

Range	Assumption
1920 - 1970	Exponential growth to weighted percentage of 1985 figure
1971 - 1985	Linear growth to 1985 figure
1986 - 1998	Linear growth to 1998 figure
1999 - 2004	Linear growth to 2004 figure

For the period 1920 to 1970, an exponential relationship was developed to show low initial growth, followed by increased growth in the last ten years before the first formal government water control was instituted (Schoeman and Joubert, 2007).

6. Typical Results

The following figures indicate typical result from using the improved WRSM2000 irrigation module. A normal exponential growth in irrigation areas is assumed. Figure 1 illustrated the effect of drought reduction factor on irrigation demand and the return flow generated by the irrigation module only. Figure 2 illustrates the same simulation, but providing the total return flow generated, which includes the natural runoff generated on the irrigation area, as described in Equation 4

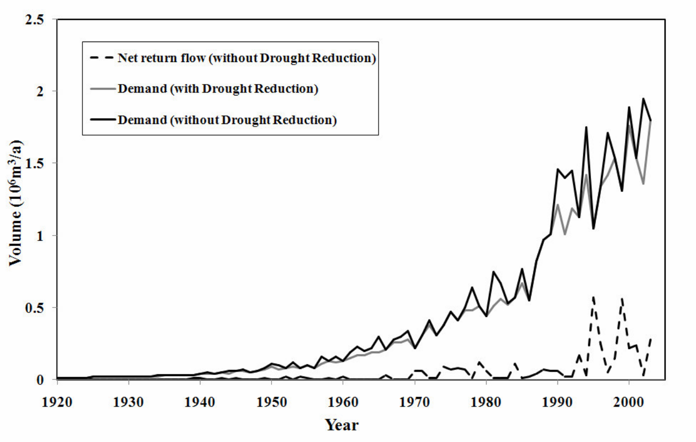

Figure 1: Irrigation demand (with and without drought reduction) and net return flows

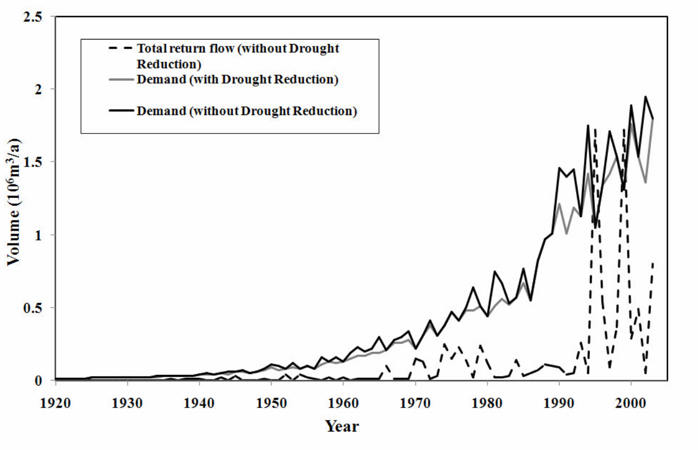

Figure 2: Irrigation demand (with and without drought reduction) and total return flows

7. Future improvements

It will be recommended to the custodians of the model that a pre-processor system be developed to manage the raw data and generate growth data for input to the WRSM2000 irrigation module. Such a system could provide national estimates for irrigation demands, given growth assumptions and spatially validated crops requirements and irrigation systems using SAPWAT data. Assumptions for the model could also then be more readily disaggregated into quinary levels.

The model could also be improved to mimic different irrigation practices, such as ignoring the effect of rainfall in irrigation demand calculations in areas where irrigators have timing systems on their pumps and irrigate even when there might be rainfall.

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