Report Title: ***Modelling Approach and Procedures for Water Availability Assessment Studies: Version 2***

Study Name: *Mhlathuze Water Availability Assessment Study*

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LIST OF STUDY REPORTS

Report Number	**Title**
PWMA 06/000/00/0407	Rainfall Data Analysis
PWMA 06/000/00/0507	Water Use, Water Requirements and Return Flows
PWMA 06/000/00/0607	Hydrology Assessment (including Groundwater and Water Quality)
PWMA 06/000/00/0707	Monitoring Assessment Report
PWMA 06/000/00/0807	Modelling Approach and Procedures for Water Availability Assessment Studies (version 1)
PWMA 06/000/00/0907	Modelling Approach and Procedures for Water Availability Assessment Studies (version 2)
PWMA 06/000/00/1007	Systems Analysis

Two modelling framework reports have been submitted as part of this study. Version 1 represents the proposed framework that was written before the start of the study, while version 2 represents the finalised framework including the experiences of all the study teams which have carried out the Water Availability Assessment studies. Version 2 is, however, still a dynamic document and will be continually updated as new experiences occur.

MHLATHUZE WATER AVAILABILITY ASSESSMENT STUDY

Modelling Approach and Procedures for Water Availability Assessment Studies

EXECUTIVE SUMMARY

The Department of Water Affairs and Forestry, Directorate: National Water Resource Planning (NWRP) has commissioned five studies on the Mhlathuze, Inkomati, Berg, Crocodile (West) and Olifants river systems, for the purpose of assessing the available water resources. The five studies, which are referred to as Water Availability Assessments (WAAs), are undertaken in support of the compulsory licensing process, an initiative which is aimed at converting existing water use entitlements into water use licenses. It consists of various steps including the registration, validation and verification of actual water use.

This document is based on a preliminary framework developed during the initial phases of the Mhlathuze WAA study to describe proposed modelling approach and procedures for WAA studies. It takes account of the coordination among the five WAA studies and the lessons learned from application of the preliminary framework. The document provides the overall principles that support the modelling approach and procedures for WAA studies and detailed technical descriptions and explanations are therefore not provided. For this purpose, references to the relevant technical documents are made throughout. The proposed modelling approach and procedures include a number of important aspects:

- *Information sources and references;*
- *Developing the representative system network model;*
- *Modelling of water use, including:*
    - *Urban and industrial water requirements and return flows;*
    - *Irrigation water requirements and return flows;*
    - *Streamflow reduction areas;*
    - *Riparian alien invasive vegetation;*
    - *Ecological water requirements;*
    - *Water use efficiency and demand management.*
- *Modelling water bodies, including:*
    - *Large dams;*
    - *Small dams;*
    - *Wetlands;*
    - *Lakes.*

- *The surface hydrology assessment;*
- *The modelling of groundwater-surface water interaction;*
- *Undertaking the water resources system analysis;*
- *The water quality assessment;*
- *Communication and information storage;*
- *Modelling confidence.*

Finally, it is recommended that this document should be adopted as a guideline for the modelling approach and procedures to be applied in WAA studies. However, in cases where the modelling approach and procedures proposed here are considered to be inadequate or inappropriate, other methodologies may be followed, with comprehensive documentation in this regard providing appropriate motivation.

MHLATHUZE WATER AVAILABILITY ASSESSMENT STUDY

Modelling Approach and Procedures for Water Availability Assessment Studies

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LIST OF ABBREVIATIONS

DSL	**Dead Storage Level**
DWAF	**Department of Water Affairs and Forestry**
EMC	**Ecological Management Class**
EWR	**Ecological Water Requirement**
FSL	**Full Supply Level**
GUI	**Graphical User Interface**
GWSWIM	**Groundwater-Surface Water Interaction Model**
IDP	**Integrated Development Plan**
IFR	**In-stream Flow Requirement**
ISP	**Internal Strategic Perspectives**
IWQS	**Institute of Water Quality Studies**
MAP	**Mean Annual Precipitation**
MAR	**Mean Annual Runoff**
NWRS	**National Water Resources Strategy**
PCD	**Pollution Control Dam**
PSP	**Professional Service Provider**
Rain-IMS	**Rainfall Information Management System**
RWQO	**Resource Water Quality Objective**
RI	**Recurrence Interval**
RWQO	**Resource Water Quality Objective**
SASRI	**South African Sugarcane Research Institute**
SAWS	**South African Weather Service**
SD	**Standard Deviation**
SI	**Seasonal Index**
STOMSA	**Monthly Multi-Site Stochastic Streamflow Model**
TDS	**Total Dissolved Solids**
WAA	**Water Availability Assessment**
WCDM	**Water Conservation and Demand Management**
WMA	**Water Management Area**
WR90	**Surface Water Resources of South Africa, 1990**
WRSM2000	**Water Resources Simulation Model 2000**
WRYM	**Water Resources Yield Model**
WRYM-IMS	**Water Resources Yield Model Information Management System**
WSA	**Water Services Authority**

WSDP	**Water Services Development Plan**
WWTW	**Waste Water Treatment Works**

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1. INTRODUCTION

1.1 Background

The Department of Water Affairs and Forestry, Directorate: National Water Resource Planning (NWRP) has commissioned five studies on the Mhlathuze, Inkomati, Berg, Crocodile (West) and Olifants river systems, for the purpose of assessing the available water resources. The five studies, which are referred to as *Water Availability Assessments* (WAAs), are undertaken in support of the compulsory licensing process, an initiative which is aimed at converting existing water use entitlements into water use licenses. It consists of various steps including the registration, validation and verification of actual water use.

1.2 Context of the Water Availability Assessment studies

One of the main aims of the five WAA studies is to develop modelling approaches and procedures that can be used for decision support in the compulsory licensing process. To this end, it is critical that the modelling approaches and procedures applied can withstand public, technical and legal scrutiny. Although the Mhlathuze study is one of five WAA studies, it was scheduled such that it preceded the other studies slightly and thereby providing a testing ground for the proposed modelling approach and procedures and a basis for making recommendations regarding their application in the other WAA studies.

In support of the five WAA studies, a detailed assessment was made of the business requirements for modelling and decision support for licensing processes. This assessment was undertaken by the DWAF Directorate: Water Resource Planning Systems through a parallel process as part of the *Maintenance and Updating of Hydrological and System Software – Phase 3* project (IS, WRP & PDNA, 2005). General business requirements emanating from the above study provided guidelines for the development of the modelling approach and procedures for WAA studies and are summarised below:

- Consistency between hydrological processes and water resource analyses;
- Consistency in the application of analysis methodologies in the different studies;
- Explicit modelling of processes in order to provide the opportunity to undertake scenario analyses of management measures. A balance is required between the availability of actual data for verification of the models and the ability to explicitly simulate the processes;
- The legal integrity of the results from the studies should be supported by thorough documentation describing all assumptions and methodologies that were applied in the availability assessments;

- Modelling will, at least initially, be undertaken at a monthly timescale;
- Effective communication to stakeholders would be essential to create confidence in the assessment techniques, assumptions and results of the modelling exercises.

The above guidelines form the bases for the proposed modelling methodology and the foundation for this report as discussed in the next section.

1.3 Purpose of document

This document is based on a preliminary framework developed during the initial phases of the Mhlathuze WAA study to describe proposed modelling approach and procedures for WAA studies. It takes account of the coordination among the five WAA studies and the lessons learned from application of the preliminary framework. The document provides the overall principles that support the modelling approach and procedures for WAA studies and detailed technical descriptions and explanations are therefore not provided. For this purpose, references to the relevant technical documents are made throughout.

Finally, in light of the particular modelling requirements of the WAA studies (as described in the previous section) the applied modelling approach and procedures, in some cases, deviate significantly from those traditionally applied in water resource assessment studies undertaken in the past. This report will serve to highlight such deviations and will thereby provide a reference of the advances that have been made.

1.4 Structure of document

This document provides detailed information on the modelling approach and procedures to be applied in WAA studies and is structured in a number of sections, each of which deals with a particular aspect. These are summarised below:

- An introduction to the document, including background and context of the WAA studies, as well as the purpose and structure of the document (this section);
- Information sources and references (**Section 2**);
- Developing the representative system network model (**Section 3**);
- Modelling water use (**Section 4**);
- Modelling water bodies (**Section 5**);
- Surface hydrology assessment (**Section 6**);
- Groundwater-surface water interaction (**Section 7**);
- Water resources system analysis (**Section 8**);
- Water quality assessment (**Section 9**);
- Communication (**Section 10**);

- Modelling confidence (**Section 11**);
- Recommendations (**Section 12**);
- References (**Section 13**).

Lists of abbreviations, tables and figures are provided at the beginning of the document and appendices may be found at the end.

2. INFORMATION SOURCES AND REFERENCES

2.1 Overview

The level of confidence that can be placed on the results of a water resource assessment study is largely dependent on the quality of the information and data that are available for the configuration of the water resources system model. The information requirements for modelling are diverse, covering time-series data such as rainfall and streamflow as well as information describing the physical characteristics of the water resources system. This includes, among other things, information on water infrastructure features such as reservoir characteristics and the capacity of water transfer conduits. In addition, other information relating to the management of the water resources is also needed and typically includes the rules and regulation for the operation of the system. This may be in the form of legal directives such as court orders or other agreements that regulate the actions of water users.

There are several processes and functions carried out by DWAF which produce information for the WAA studies. The licensing of water use is an initiative aimed to convert existing water use entitlements into water use licenses and consists of various steps including registration, validation and verification. The products of these processes are water use databases which give, among other things, the spatial location, land coverage (i.e. land use such as irrigation) and the volume of water use of individual water users. A second process providing information to WAA studies is the determination of the Ecological Water Requirements (EWRs) which are provided in the form of distribution curves that define the flow required in a river system to achieve a particular ecological status. The products of both the above described activities form essential sources of information for the WAA studies.

An important consideration in formulating the water resource system models is that all information of relevance should be analysed and considered for possible use in the study. The analysis of the information should include comparisons either from different sources or using references from reports of previous studies. The analysis and comparisons should culminate in a description of what information has been adopted for the study and should be supported by sound reasoning and motivations for the selection. The omitting of relevant information may results in the configuration of a model that misrepresents the physical (“real world”) water resource system.

The following section provides the information requirements for modelling and **Section 2.3** describes sources of information and data. Finally the section is concluded with a short commentary on references and the need for comparisons of data.

2.2 Information requirements for modelling

Information and data required for WAA studies could loosely be grouped into primary and secondary information. Primary information would typically be actual measurements, such as records of daily or monthly rainfall, streamflow gauge records and reservoir basin survey data. Secondary information would be where further manipulation of the information was carried out, such as patching of rainfall data or reservoir characteristics that have been converted into the format required by the water resources model in question. When using secondary information it should be borne in mind that this information has been subjected to change and manipulation. Although thorough checking of all information is required irrespective of whether it is primary of secondary, secondary data should be analysed in view of what the initial purpose of the application was and what the intended use of the information will be in the WAA study. This may lead to the use of the information as is, or a decision rather to source the original primary information.

Table 2-1 provides a list of information and data requirements for a typical WAA study. The requirements are grouped according to the generic processes of WAA studies and a brief description is given to explain the context and purpose of the information.

Table 2-1: Information requirements for modelling

Description of Information / data	Format	Purpose and application
Hydrological information		
Rain gauge data	Time-series of daily or monthly data in millimetres	Rainfall-runoff modelling, irrigation water requirements, reservoir water balance
Evaporation data	Monthly time-series data in millimetres	Rainfall-runoff modelling, irrigation water requirements, reservoir water balance
Streamflow gauge data	Daily or monthly time-series data expressed as volume over time	Rainfall-runoff modelling
Maps of river system and catchments	GIS and/or printed maps at appropriate scales	Defines the water resource system layout and configuration
Characterisation of ground-water surface water interaction	Parameters of groundwater simulation model	Simulate the effect of groundwater abstraction on surface water availability
Water requirements and return flows		
Land use data	GIS coverage indicating the area and type of land use, aerial photography and satellite imagery	Estimating the water use of different land use activities, naturalisation of hydrology, scenario analysis of water availability
Estimates of land use based water requirements	Calculated water use based on crop (vegetation) water requirement data, evapo-transpiration and rainfall	Rainfall-runoff modelling, water availability analyses through scenario assessments

Description of Information / data	Format	Purpose and application
Metered supply and return flow data	Daily or monthly time series data of recorded flows	Rainfall-runoff modelling determines historical trends, basis for future demands and return flow estimates
Ecological water requirements	Monthly flow distributions, one for each month of the year	Simulation of the ecological water requirements for scenarios of different Ecological Management Classes (EMCs)
Water resource analysis		
Stochastic flow and rainfall data	Model generated flow and rainfall time series	Estimation of the assurance of supply or risk of supply failures
Reservoir characteristics	Elevation, volume and surface area relationship tables and operating levels	Water balance simulation
Conveyance conduit characteristics	Capacity of structure of basic hydraulic characteristics	Simulation of water resource system's physical constraints
Water supply and operating rules	Narrative and/or schematic representation of rules	Configuration of water resources model to represent current applied conditions
Reliability of supply criteria	Fractional categorisation of water requirement volumes and associated reliability criteria	Measure of establishing compliance in supply (success or failure) when scenario analyses are undertaken

2.3 Information sources

Information and data can be obtained from various sources as presented in **Table 2-2**.

Table 2-2: Information sources for modelling

Description of Information / data	Description of sources
Hydrological information	
Rain gauge data	▪ South African Weather Service (SAWS); ▪ Research institutions; ▪ Private weather stations owners; ▪ DWAF weather stations usually at dams; ▪ Databases such as the Rain-IMS of DWAF – contains monthly data.
Evaporation data	▪ WR90 publications; ▪ South Africa Weather Service; ▪ DWAF weather stations, usually at dams.
Streamflow gauge data	▪ Directorate: Hydrology of DWAF; ▪ Research institutions.
Maps of river system and catchments	▪ DWAF GIS databases; ▪ Research institutions.

Description of Information / data	Description of sources
Characterisation of groundwater surface water interaction	▪ Studies undertaken by DWAF to characterise the groundwater resources of the country; ▪ Reports of groundwater investigations in the specific catchment from DWAF or other sources; ▪ Publications from research institutions.
Water requirements and return flows	
Land use data	▪ Data from DWAF's Validation and Verification process; ▪ Primary data capturing using aerial photography and/or satellite imagery; ▪ Field work by capturing data using Global Positioning Systems.
Estimates of irrigation water requirements	▪ Application of crop water requirement calculation software such as SAPWAT; ▪ Sector specific water requirement estimation software such as SAshed – applied by the South African Sugar Research Institute.
Estimation of the water use by streamflow reduction processes	▪ Information produced in collaboration with the forestry sector using the ACRU modelling system (see **Section 4.4** for more details); ▪ Historically (in the past) streamflow reductions were estimated using models such as AFFDEM.
Metered supply and return flow data	▪ Directorate: Hydrology of DWAF; ▪ Water Service Providers such as municipalities, water boards, mines, industries and private water users.
Ecological Water Requirements	▪ DWAF Directorate: Resource Directed Measures maintains a countrywide database of results from reserve estimation studies; ▪ In areas where information is not available from the database reserve estimation studies should be carried out to provide the nessasary information.
Water resource analysis	
Reservoir characteristics	▪ Directorate: Hydrology of DWAF maintains a database of all the reservoir basin surveys; ▪ The DWAF Regional Offices is a source of Information on smaller dams.
Conveyance conduit characteristics	▪ Engineering design report; ▪ White Papers that describe the water resource infrastructure; ▪ Pumping tests particularly if the infrastructure is aged.
Water supply and operating rules	▪ Regional Office personnel responsible for system operations; ▪ System analysis reports.
Reliability of supply requirements or criteria	▪ System analysis reports; ▪ Decisions (selection) by the water users, water service providers and system operators.

2.4 References and comparisons

Reports and documentation of previous water resource studies, situation assessment studies, feasibility studies, White Papers and planning activities are essential sources of information that need to be reviewed with the aim to extract all relevant information. Most water resource systems and river catchments have been the subject of several investigations in the past and the documentation gives a trail of the historical development and versions of data on surface runoff, rainfall and evaporation to mention a few.

Comparison of data and information among previous studies as well as comparison with the results of the current assessment should be carried out and documented. The objective of such comparisons is to highlight differences and similarities as well as provide reasons and motivation for selecting information and data that are considered to be acceptable for the study at hand. Comparison of data and information for an evaluation of consistency is also essential. For example, comparisons of electronic data with summaries in reports give the assurance that the correct version of the electronic data is being used – or highlight differences that need to be resolved.

Consistency checks when applying system model is a valuable means of ensuring compatibility with previous work. As an example, at the start of a study verifying that the same historical firm yield is obtained as published in a previous study report, provides the confidence that the data set (system configuration, operating rules and hydrology) now being used are the same as what was used in the previous investigation.

3. DEVELOPING THE REPRESENTATIVE SYSTEM NETWORK MODEL

Developing a representative network model for a water resource system involves process whereby the modeller creates a synthetic representation of reality, in the form of a schematic diagram. This is achieved by indicating the connectivity between and nature of the various components that make up the system in question. This process of synthesis, however, always implies a trade-off between the need to simulate the behaviour of individual system components at a sufficient level of detail, on the one hand, and practical modelling limitations on the other.

The process of developing a representative system network model includes three main aspects, (a) the identification of physical system features, (b) assessing the appropriate spatial resolution and (c) the lumping and aggregation of system components until the appropriate spatial resolution is achieved. These aspects, within the context of the WAA studies, are discussed in the following sections.

3.1 Identifying physical system features

The starting point in the process of developing a representative water resource system network model is usually a geographical map showing the physical features of the system in question. The map should denote rivers, catchment boundaries, reservoirs, abstraction works, water discharge infrastructure, water transfer conduits (canals, tunnels or pipelines), the location of water users, etc.

The catchment delineations, required for defining the way in which net runoff from incremental sub-catchments enter the system network, are determined from the map. The selection of incremental sub-catchment boundaries within the system is dictated by the spatial resolution to which modelling needs to be undertaken, position of existing infrastructure, as well as the location of potential new water resource development options that have to be assessed.

3.2 Spatial resolution

In general, past system analysis studies focused mainly on determining the yield of systems consisting of one or more reservoirs. This focus allowed defining relatively large catchments for which the hydrology was developed. Land use impacts and abstractions and return flows were simulated by lumping elements together, e.g. dummy dams were created in the system networks to represent the combined impact of several discrete farm dams.

The focus of the WAA studies is, however, different where the emphasis is on simulating local catchments and tributaries in order to reflect the impacts water users (or groups of water users) have on one another. The objective is therefore to configure the system models at a sufficient resolution to be able to identify problem areas (over-allocation) in river systems as well as areas where there is surplus water available. The method of assessing the water availability involves evaluating the reliability of supply to all water users in the network model on an individual basis. The selection of the resolution will therefore depend on several characteristics of the particular system being analysed. Aspects to consider in the definition of the network model are listed below:

- The resolution should be dictated by system specific layout and pre-defined modelling should not be followed;
- As a minimum, each quaternary catchment should be represented by a node in the network system;
- Users receiving water from tributaries and from the main stream of a river should be analysed separately in order to evaluate local availability;
- Differences in hydrological and climatic conditions;
- The location of farm dams and water use abstractions;
- The resolution should allow for assessment of the downstream impacts of one group of water users on another.

3.3 Lumping and aggregation of system components

It is inevitable that some abstractions and farm dams will have to be combined and simulated as lumped network elements. Water abstractions of the same type that has access to the same surface flow should be grouped and be represented by a single abstraction channel. Farm dams located in tributary catchment should be combined to form single dummy dams in the network model. This is required due to the large number of farm dams in certain catchments which will not be practical to simulate individually. Consideration should be given to simulate larger key dams individually, especially if they are used to supply primary water users for domestic purposes.

Summarised presentations of water availability will be required to reflect the overall water supply situations in catchments. Methods of aggregating the results of the abstractions must be employed to provide concise results of the status of supply.

4. MODELLING WATER USE

4.1 Overview

The modelling of water use in WAA studies involves many processes and the application of various software utilities and water resource modelling tools. Very important among these are the following:

- The enhanced *Water Resources Simulation Model 2000* (WRSM2000), which is a rainfall-runoff model applied in the hydrological calibration and naturalisation processes.
- The *Water Resources Yield Model* (WRYM), which is a network simulation model used to analyse complex water resource systems in order to assess their long- and short-term resource capability (yield).
- The *Water Resources Yield Model Information Management System* (WRYM-IMS), which was recently developed to improve the performance and ease of use of the WRYM by providing a database to manage WRYM data sets, as well as an interface which allows for system configuration and run result interpretation through a graphical user interface (GUI).

More information on the application of these models in WAA studies is provided in **Sections 6** and **8** and details on their configuration and testing may be found in:

- *WRSM2000 (Enhanced) User's Guide* (SSI, 2006);
- *Water Resources Yield Model User Guide – Release 7.5.6.2* (DWAF, 2008);
- *Water Resources Yield Model: Procedural Manual*, for model version 4.1.1 (DWAF, 2005a);
- *WRYM-IMS Help System* (DWAF, 2005b).

4.2 Urban and industrial water requirements and return flows

The methodology proposed for urban and industrial requirements involves the following steps:

- Identify all water demand centres, sources and discharge locations of return flows based on the layout of the water supply system and the sources of water that supply the requirements.
- Collect current and historical actual water use and return flow information (quality and quantity), as a first priority. Most industries are metered and information can be obtained from the industries directly or from their water services provider. Water requirements data for the urban sector can also be obtained from the applicable water services authority or provider as the information is used for bulk or individual billing, planning and

operational purposes. However, difficulty will exist where there are un-metered areas and no effective billing system. DWAF also keeps record of water use throughout the country. However, caution should be exercised in differentiating the water abstracted from the resource for treatment and actual urban and industrial water requirements. Projected water use and return flow estimates should be collected as well, where available.

- Develop a spreadsheet database with collected current and historical information from different sources and make allowance for inclusion of actual future water use as it becomes available.
- Compare data from different sources and identify discrepancies in the collected data and make decisions on the preferred data sets for use in the WAA study.

Where information is not available, requirements may be calculated as described below.

a) Urban requirements

- Define the water demand centres and group them to reflect the layout of the water supply system and the sources of water that supply the requirements.
- Define the water services categories applicable to the area and associated demographics information, then determine and apply the typical per capita per day water use to estimate requirements for each category.
- Define the unavoidable bulk and reticulation water losses and include them as a requirement that must be supplied from the water resource. For this purpose, any area-specific *water conservation and demand management* (WCDM) strategy, plan or programme must be taken into consideration.
- Should future projections be required:
  - Obtain historical water requirements and determine annual growth percentages and the drivers of growth;
  - Obtain and apply the future socio-economic / demographic information on the drivers of growth and estimate the water use;
  - Obtain information on the growth potential and planned developments for the area in question and quantify the associated water requirements as stated above;
  - Due to uncertainties associated with future development and socio-economics in the urban sector, define several (at least 3) potential growth scenarios to reflect area specific developmental intervention and potential WCDM measures, and select the most probable scenario/s for use in current and future requirements determination. Use the highest and lowest potential growth scenarios for scenario planning to present the lower and upper growth envelopes.

b) Industrial requirements

- Obtain water requirements from the industries in the area from water services development plans (WSDPs), water services authorities (WSAs) and applicable regulatory bodies. Industrial production processes and water use differ from industry to industry and the best source of data is the actual metered water use for each industry or bulk meter data supplying industrial zones.
- The future water use for industry will be driven by growth and change in processes, therefore establish the growth prospects and link them to current and future potential water use efficiency or industry's WCDM strategy, which should be based on the applicable industrial sector benchmarks and DWAF licence conditions.

c) Return flows

- Define sources and locations of return flows and their actual discharge points into the river or sea system.
- Obtain actual inflow volumes into the waste water treatment works (WWTW) and their discharges (quality and quantity) into the river or sea system. Industries may have their own treatment works and discharge directly into the river or sea system. Information will therefore need to be obtained from each industry identified as a source of return flows.
- Where only the inflows into the treatment works are available, obtain information on the treatment process and conveyance losses, amount of effluent re-used and perform a water balance to determine the discharges into the river or sea system.
- Should future projections be required:
    - Establish the relationship between the current water use and return flows;
    - Establish the timelines of the industry's WCDM programme for effluent re-use and water use efficiency improvements;
    - Reconcile the above two and determine the future return flows. The WCDM programme introduces uncertainties in the timing and selection of identified intervention measures, and this therefore necessitates the use of several scenarios to determine the future return flows.
    - Define the return flows scenarios to mirror the defined water use scenarios and / or the WCDM strategy.
- Produce a table and files of water use requirements and return flows in a format that can be used in a model. The information should therefore be grouped according to the system network definition in question.

A detailed guide in the estimation of urban and industrial water requirements may be obtained from the following sources:

- The *National Water Resources Strategy* (NWRS);
- Studies undertaken by the DWAF, Directorates: National Water Resource Planning and Water Resource Planning Systems;
- The document *Return Flow Model User Guide* from the *Crocodile (West) River Return Flow Analysis Study* (DMM, LSE & WRP, 2004).

Area-specific information for use in the estimation of urban and industrial requirements and return flows may be obtained from the following sources:

- Census data;
- Water services development plans (WSDPs) and integrated development plans (IDPs);
- Water conservation and demand management (WCDM) strategies;
- Internal strategic perspectives (ISPs).

4.3 Irrigation water requirements and return flows

The methodology proposed for modelling the irrigation water requirements and return flows for an irrigation area in WAA studies involves five main steps and these are summarised below:

- **Step 1**: Apply SAPWAT to obtain *monthly evapo-transpiration* specific to each crop associated with the irrigation area under consideration.

- **Step 2**: Calculate the *total annual irrigation requirement (excluding losses)* for the irrigation area under consideration, using a spreadsheet. Input to this calculation includes the evapo-transpiration data obtained from Step 1.

- **Step 3**: Apply the *Annual Irrigation Return Flow Model* (AIRFM) to make improved estimates of the *total annual return flow volume* for the irrigation area under consideration. Input to the AIRFM includes the total annual irrigation requirement (excluding losses), obtained from Step 2.

- **Step 4**: Use the Irrigation Block sub-model, which has been incorporated into the enhanced WRSM2000 model, to *model irrigation water requirements and return flows* in the calibration and naturalisation process. Input to the Irrigation Block includes evapo-transpiration data obtained from Step 1 and the *total annual return flow volume* obtained from Step 3.

  It should be noted that return flows modelled in the Irrigation Block are controlled by means of a *Return Flow Factor* and that this factor is adjusted by the user, in an iterative process, until the desired return flow volumes are achieved. Furthermore, two options are available in WRSM2000 for the routing of flows through the Irrigation Block return flow channel, as outlined below:

- *Net Return Flow*-option: Flows represent the amount of return flow generated as a direct result of the irrigation;
- *Total Return Flow*-option: Flows represent the total of (1) the amount of return flow generated as a direct result of the irrigation applied and (2) the runoff that would have been generated under natural conditions by the irrigated catchment area. In this regard, the natural catchment area is reduced by the irrigation block area so as not to double count for the rainfall falling on the irrigation area.

For the purpose, therefore, of determining an appropriate value for the *Return Flow Factor*, the *Net Return Flow*-option must be selected.

- **Step 5**: Use the Irrigation Block sub-model, which has been incorporated into the WRYM and WRYM-IMS, to *model irrigation water requirements and return flows* in the yield assessment process.

  The above procedure is similar to that of Step 4. A recalibration of the *Return Flow Factor* is not required and the relevant value as determined in the WRSM2000 analysis may simply be applied in the WRYM. It should be noted, however, that the modelled flows through the Irrigation Block return flow channel may differ from those in the WRSM2000 since the WRYM always models Total Return Flows (as described earlier)

A detailed description of the methodology for modelling irrigation water requirements and return flows using the models mentioned above is provided in the following documents:

- A guide to the application of SAPWAT can be found in the *SAPWAT User's Manual* (Van Heerden & Crosby, 2002);
- A conceptual description of the AIRFM is provided in the document *Relationship Algorithms and Calibration* (DMM, LSE & WRP, 2004a) and a user guide is incorporated with *Return Flow Model User Guide* (DMM, LSE & WRP, 2004b);
- Algorithms applied in the original *Water Quality and Sulphates* (WQS) model's Irrigation Block sub-model are described in Section 4 of the document *Water Quality Modelling – Volume A: Water Quality Calibration Model* (BKS, 1988), with a modification as detailed in Section 2.2.4 of *Hydrological Business and Functionality Improvement Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2005).
- Application of the Irrigation Block in the WRYM and WRYM-IMS is described in Appendix B of the supporting document *Hydrological Business and Functionality Improvement Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2005)

4.4 Streamflow reduction areas

4.4.1 Overview

The methodology to be applied in WAA studies for the modelling of streamflow reduction (SFR) areas is presented in this section with information relating to specific SFR land cover types provided in **Sections 4.4.2** to **4.4.4**. These types are:

- Commercial forestry;
- Dry-land sugarcane;
- In-catchment alien invasive vegetation.

In this regard, it should be noted that "in-catchment" alien invasive vegetation refers to those located in mountain catchment areas and that a different approach is required for the modelling of vegetation located in the riparian zone. The amount of water used by the latter depends (among other things) on the amount of flow available in the river and therefore differs from that of in-catchment vegetation. The modelling of riparian alien invasive vegetation is discussed in **Section 4.5**.

The basic methodology for modelling SFR areas involves three steps as summarised below:

- **Step 1**: Obtain estimates of the reduction in runoff caused by the SFR area under consideration, including the impact on annual (or average) flows and the impact on low flows. These estimates will serve as the *long-term SFR targets* to be used as a basis for the modelling of SFR areas in the enhanced WRSM2000 model (in Step 2).

- **Step 2**: Apply the enhanced WRSM2000 to *model the impact of SFR areas* in the hydrological calibration and naturalisation process. The enhanced WRSM2000 uses a new methodology for modelling SFR areas which was developed in consultation with Dr WV Pitman. More information in this regard is provided below.

- **Step 3**: Use the new *SFR sub-model* in the WRYM and WRYM-IMS to *model the impact of SFR areas* in the yield assessment process. More information in this regard is provided below.

The new methodology for modelling SFRs in the enhanced WRSM2000 is based on the principle that portions of the modelled catchment may be covered by specific SFR land-use types and that the remainder of the catchment is classified as "natural". The natural portion of the catchment is modelled by means of a principle runoff module which is referred to as a "Master". Each SFR portion is modelled as an individual entity and represented by a separate runoff module called a “Slave”. The Pitman calibration parameters for each “Slave” are derived from that of the “Master” and adjusted through an automated procedure which attempts to achieve a long-term SFR target, such as determined in Step 1 above.

The new *SFR sub-model* in the WRYM and WRYM-IMS is based on the utilisation of a number of new time-series data files. These time-series, all of which are obtained as a direct output from the modelling undertaken with the enhanced WRSM2000 model in Step 2 above, are listed below:

- A time-series data file containing monthly unit runoff (in units of mm), for each SFR catchment portion modelled in the system network. The data in this file are used for the calculation of the monthly runoff volume for the SFR portion in question.
- The *.S-file, which contains monthly values of total soil moisture (or S) (in units of mm), for the natural portion of the sub catchment (i.e. the portion which is not covered by an SFR land cover type).
- A time-series data file containing monthly values of total soil moisture (or S) (in units of mm), for each SFR catchment portion.

With regard to the above, it is important to note that S-time-series data files will only have to be provided for incremental sub-catchments in the WRYM system network where groundwater-surface water interaction is modelled using the *Groundwater-Surface Water Interaction Model* (GWSWIM), as discussed in **Section 7**. However, the GWSWIM will only be implemented in a later version of the WRYM and S-time-series are therefore not required for the current version of the model.

A detailed description of application of the new SFR sub-model in the WRYM and WRYM-IMS is provided in Appendix C of the supporting document *Hydrological Business and Functionality Improvement Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2005). SFR target information may be obtained from any preferred source, including the Gush Study (Gush et. al., 2002), the CSIR runoff reduction curves published by Scott and Smith (1997 and 2002) or newly-generated ACRU simulation results. A decision in this regard may depend on the requirements of the particular study in question, however, recommendations and motivations on appropriate data sources for WAA studies for commercial forestry, dry-land sugarcane and in-catchment alien invasive vegetation are discussed in the following sections.

4.4.2 Commercial forestry

The impact of commercial forestry may be modelled in WAA studies based on the methodology described in **Section 4.4.1** for SFR areas. It is recommended that SFR target information for commercial forestry be adopted from the results of the Gush Study (Gush et. al., 2002) and a motivation for this is provided below:

- The aim of the research undertaken by Gush was to improve the previous CSIR forestry curves with respect to catchments with “lower” rainfall areas. The Steering Committee that lead the Study accepted the results as an improvement on the CSIR curves.
- The results from the Gush Study have been extensively discussed with the forestry industry and representatives of the industry were involved in the definition of the parameters used in the ACRU modelling. The results are therefore generally accepted.

More information in this regard may be obtained from Appendix C, Section (b) of the supporting document *Hydrological Business and Functionality Improvement Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2005).

4.4.3 Dry-land sugarcane

The impact of dry-land sugarcane may be modelled in WAA studies based on the methodology described in **Section 4.4.1** for SFR areas. It is recommended that SFR target information for dry-land sugarcane be obtained based on ACRU simulations, similar to those undertaken in the Gush Study for forestry (see **Section 4.4.2**). Preliminary ACRU analyses were carried out and show promising results. However, in order to obtain the buy-in of the sugar industry, representatives from the South African Sugarcane Research Institute (SASRI) will have to be consulted in this regard.

4.4.4 In-catchment alien invasive vegetation

The impact of in-catchment alien invasive vegetation may be modelled in WAA studies based on the methodology described in **Section 4.4.1** for SFR areas. It is recommended that SFR target information for in-catchment alien invasive vegetation be obtained based on the CSIR vegetation runoff reduction curves, produced by Scott and Smith (2002). These curves are used by the Working for Water programme to plan future activities and are generally accepted by stakeholders. The Scott and Smith methodology allows for the following variables:

- Location of alien plants by distinguishing between:
  - Plants in riparian zones;
  - Plants in mountain catchment areas (the latter should be used).
- The biomass characteristics of the vegetation must be defined and are represented by three variables:
  - An equivalent dense area;
  - Biomass class (tall trees, medium trees and tall shrubs);

  - The age of each of the biomass classes as listed above.

Finally, in cases where the vegetation in question is black wattle, the possibility may be considered of using target SFR information from the Gush Study, instead of the Scott and Smith curves, on the basis that the impact of such vegetation may be comparable to that of commercial forestry.

4.5 Riparian alien invasive vegetation

The methodology to be applied in WAA studies for modelling the water use by alien invasive vegetation is presented in this section. The methodology, which was recently developed by Dr WV Pitman as part of the WR2005 study, has been incorporated as the new *riparian alien invasive vegetation sub-model* into the enhanced WRSM2000 model, for use in the hydrological calibration and naturalisation processes. This sub-model has, however, not yet been incorporated into the WRYM and WRYM-IMS for use in the yield assessment process. It is therefore recommended that, for this purpose, the modelled time-series of water use by riparian alien invasive vegetation be obtained from the WRSM2000 model run and imposed on the WRYM system as a requirement using the existing *specified demand channel*-type.

A summary of the basic principles of the *riparian alien invasive vegetation sub-model* is presented below. In this regard, it should be noted that, as mentioned in **Section 4.4**, which deals with the modelling of streamflow reduction (SFR) areas, riparian alien invasive vegetation may not be modelled as an SFR (as is the case with in-catchment vegetation) since the amount of water used by such vegetation depends (among other things) on the amount of flow available in the river and therefore differs from that of SFRs.

- Vegetation in the riparian zone has access to additional water, i.e. seepage to or from the stream channel.
- Alien invasive vegetation is first modelled as if not in the riparian zone and further adjustments are then made to account for additional water loss, as follows:
  - For each month, the actual evapo-transpiration is calculated and compared with the potential rate;
  - The difference between actual and potential represents the remaining “crop demand” of the alien invasive vegetation;
  - 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 invasive vegetation.

A detailed description of the methodology for modelling alien invasive vegetation in WAA studies is provided in the supporting document *Alien Vegetation in Riparian Zone*

(Pitman, 2005).

4.6 Ecological water requirements

The modelling of ecological water requirements will be required in WAA studies as part of the yield assessment process. For this purpose, the existing WRYM *IFR channel*-type will be used which allows for in-stream flow requirements (IFRs) to be imposed on a water resource system by means of a special IFR release control mechanism. For each IFR release control mechanism, a data table is populated which defines a reference flow-vs.-IFR-relationship for each of the twelve calendar months of the year (from October to September). The reference flows in this relationship represent the sum of the incremental hydrological inflows to one or more selected reference nodes in the system and the inflows may represent either one of the following:

- Natural runoff, i.e. flows that would have occurred had there been no human developments;
- Developed runoff, i.e. natural runoff minus the impacts of upstream diffuse water requirements and streamflow reductions.

Finally, the IFR mechanism in the WRYM also allows for a delay of up to 12 months to be defined, in which case the average hydrological inflows over the specified delay period is used as the reference for calculating the corresponding IFR release in the month under consideration.

It should be noted that two important tools have recently been developed by the DWAF, Directorate: Water Resource Planning Systems to assist modellers in the configuration of IFR release control mechanisms in the WRYM and to interpret related analysis results. These are:

- A pre-processor to use information from models such as the *Spatial and Time-series Information Modelling* (SPATSIM) *Decision Support System* (DSS), to generate data in the appropriate format for populating the WRYM IFR release control mechanism.
- WRYM-IMS features for the presentation of information on the configuration and analysis results associated with the IFRs applied in a particular scenario. More information in this regard is provided in **Section 10.2.1**.

A detailed description of the methodology for modelling IFRs in the WRYM and WRYM-IMS, as well as information regarding the tools proposed for the configuration of the WRYM and the interpretation of analysis results (as mentioned previously) is provided in the supporting document *Detailed Business Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2006a).

4.7 Water use efficiency and demand management

Modelling the possible impacts of water use efficiency and demand management will be required in WAA studies as part of the yield assessment process. However, there is no fixed or preferred model for assessing these impacts and decisions in this regard are made following assessments by specialists using a wide range of information sources, national and international benchmarks, local operating conditions, status of the water resources, socio-economic conditions and any other relevant data. It is extremely important that experienced specialists are therefore involved in the assessments of water use efficiency and demand management since there are no fixed formulae or rules, rather informed considerations on a multitude of independent and related factors.

The methodology proposed for the assessment of water use efficiency and demand management considerations will therefore involve, but is not limited to the following:

- Developing a general understanding of the water usage and requirements (current, historical and future), efficiency and return flows in relatively homogeneous areas and how this will change if combinations of *water conservation and demand management* (WCDM) measures are implemented.
- Identifying the uses of water, the different industrial and mining processes that use water, irrigation methods, mechanisms of supplying and distributing water and establishing the available best practices for different water uses and associated processes.
- Establishing the cost of water and benefits derived from the use of water.
- Establishing whether the cost of water and amount used are in line with best practice and, where they are not, motivate for changes in usage patterns or implementation of appropriate demand management strategies or WCDM investigations. The water use efficiency cannot be properly ascertained without knowing the exact processes and how much water is used under each process or sub-process, as well as the source of water. To ascertain the water use efficiency for a specific user, the cost of water and quantity of water used to produce the final products and benefits should be evaluated under the processes in question.
- Undertaking conceptual investigations or situation assessments regarding the effect of WCDM measures on the magnitude of the water requirements and return flows using available data and information on agricultural, industrial, urban, mining and any applicable water use category.
- Developing relationships that could be used to undertake yield modelling scenarios, covering the potential agricultural, industrial, urban and mining sectors WCDM measures.

- Given the water requirements for all identified water users, applicable return flows (where appropriate) and the network definition in the WRYM, the water balance of the system at each abstraction location should be determined for both surface and groundwater resources, where applicable.
- Scenario planning should be undertaken by running the WRYM under a range of scenarios, which will typically consist of variations on the combinations of water use scenarios. After running the WRYM, water balance information should be compared to make recommendations on the prioritisation of water use scenarios. The scenarios could include variations of the following variables:
  - Current requirements and return flows, as well as plausible projections for a future development level;
  - Implementation of potential water use efficiency and demand management measures and their impacts;
  - The impact of applying different ecological management classes (EMCs);
  - Changes in the water use patterns from groundwater resources, where applicable;
  - Changes in system configuration;
  - Changes in operating rules.

Additional information on the water use efficiency and demand management may be obtained from the following sources:

- Area-specific and relevant previous studies;
- The *National WCDM Strategy Document* and sector-specific *WCDM Strategy Documents* (DWAF, August 2004);
- *Performance Indicators for Water Supply Services*, IWA Publishing Manuals of Best Practices Series 2000 (Alegre et. al., 2000);
- *BENCHLEAK*, *SANFLOW* and *PRESMAC User Guides*, South African Water Research Commission Reports TT 159/01, 109/99 and 152/01, respectively. (McKenzie & Lambert, 2001);
- *Managing and Reducing Losses from Water Distribution Systems: Manuals 1-10* by the Queensland Environmental Protection Agency and Wide Bay Water;
- *Water Demand Management Cookbook: Managing Water for African Cities*, United Nations Human Settlement Programme (McKenzie, Buckle, Wegelin & Meyer, 2003).

5. MODELLING WATER BODIES

5.1 Large dams

Impoundments have the capability of retaining water over time and the simulation of their behaviour, both in the enhanced WRSM2000 and WRYM models, involves a simple calculation relating to the volume of stored water in the impoundment at the end of each simulation time-step (month). If the storage volume in the reservoir is known at the beginning of the simulation period, then the storage at the end of the first month can be calculated based on the change in storage that has occurred. The latter is calculated based on a simple mass balance principle, represented by the following formula:

$$\Delta S = Inflows - Outflows$$

Where:

ΔS = change in storage over the month

Inflows = inflows into the impoundment over the month

Outflows = outflows from the impoundment over the month

A second principle is applied in order to provide a link between the state of storage in the first and second months. The principle states that the storage in the reservoir at the beginning of any month must be equal to the storage in the reservoir at the end of the preceding month. By applying this principle, the start storage for the second month may be determined. Similarly, applying both these principle, in turn, to every month in the simulation period, the storage in the impoundment may be determined at any point in time.

Furthermore, impoundments are defined in the WRSM200 and WRYM models by means of a large number of variables relating to its physical and operational characteristics (only in the WRYM). These include:

- A description (e.g. the name of the reservoir or dummy dam);
- The full supply level (FSL), the dead storage level (DSL) and bottom level;
- A defined relationship between elevation, storage capacity and surface area;
- The water level in the reservoir at the start of the analysis;
- Rainfall and lake evaporation values (see **Sections 6.1.1** and **6.1.2**);
- Defined storage zones for the purpose of controlling the way in which it is drawn down;
- Defined operating rules.

5.2 Small dams

Small dams are known to impact on the hydrological behaviour of catchments, primarily through their storage capability and associated evaporation losses. It is therefore important to take these dams into account when undertaking hydrological and water resource modelling. However, it is generally impractical to model each of these small dams individually and they are therefore combined (or “lumped”) to form a single representative system element, or “dummy dam”. The location and size of each dummy dam is determined by the modeller based on the desired spatial resolution of the model (as discussed in **Section 3.2**) and are then modelled in the enhanced WRSM2000 and WRYM in the same way as large dams.

However, the process of lumping small dams must be undertaken in such a way that the impact of the resulting dummy dam mimics the combined impact of the individual dams it represents. A number of alternative methodologies are used for this purpose and may be applied in the WAA studies. The most common, which may be referred to as the *standard methodology*, involves the assumption that the capacity of a small dam is directly related to the size of its inflows, and, by implication, that the individual dams in a catchment would fill in equal percentage increments of their full supply volume. Many modellers opt for this approach since it produces curves of total storage capacity vs. surface area that are very similar in shape to that of single dams.

However, in a paper presented at the 13th SANCIAHS Symposium (De Jager, et. al., 2007) a *new methodology* was proposed which is based on the assumption that small dams empty as a result of evaporation from their exposed water surfaces. The latter was found to produce curves of total storage capacity vs. surface area for dummy dams that are very different in shape to those using the standard methodology. Most importantly, this results in a smaller surface area for a given volume which, when used in a hydrological model, will result in lower simulated evaporation losses. Within this context, the authors hypothesise that, under certain circumstances, the new methodology would result in the more realistic modelling of hydrological dummy dam behaviour.

5.3 Wetlands

The methodology to be applied in WAA studies for modelling wetlands was developed by Dr WV Pitman as part of the WR2005 study and is based on the original wetland algorithm from WRSM2000. It has been incorporated as a sub-model into the enhanced WRSM2000 model, for use in the hydrological calibration and naturalisation processes, as well as the

WRYM and WRYM-IMS for use in the yield assessment process. A summary of the basic principles is presented in the remainder of this section.

The original WRSM2000 wetland algorithm comprises an in-channel storage with a nominal storage volume and surface area, which can be exceeded during high flows. This operates in a way that is similar to a reservoir, where downstream flow takes place only when the (nominal) storage capacity of the wetland is exceeded. This configuration, however, was not considered to be realistic in the case of wetlands comprising a defined channel that meanders through the wetland area, feeding it with water only when the river channel capacity is exceeded. In such cases, the flow of water between channel and wetland can be in the form of over-bank spillage, or via channels, or a combination of the two. The new wetland model is therefore designed to simulate a wetland that is either in-channel or off-channel and can also be employed to simulate the effect of a man-made off-channel storage dam used for water supply.

A detailed description of the methodology for modelling IFRs in the WRYM and WRYM-IMS is provided in Appendix D of the supporting document *Hydrological Business and Functionality Improvement Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2005). Also, further information regarding preliminary tests undertaken on the new sub-model can be found in the document *Modified Wetland Sub-Model (Including Simulation of Off-channel Storage)* (SSI, 2005).

5.4 Lakes

The methodology to be applied in WAA studies for modelling wetland was recently developed by K Sami and has been incorporated as the *Lake-Groundwater Interaction Sub-model* into the *Groundwater-Surface Water Interaction Model* (see **Section 7**). The sub-model attempts to encompass the water balance of lakes that interact with regional groundwater, essentially modifying the runoff characteristics of river streams discharging from the lake.

The processes simulated include:

- The lake area and level that varies as a function of volume;
- Rainfall and evaporation from the lake area variable;
- Abstraction from fresh water lakes;
- Surface runoff into the lake;
- Surface outflow from the lake as a function of lake level and inflow;

- Groundwater seepage into and out of the lake.

A detailed description of the *Lake-Groundwater Interaction Sub-model* (Sami, 2006a) is provided in **Appendix B**.

6. SURFACE HYDROLOGY ASSESSMENT

6.1 Hydro-meteorological data analysis

The analysis of hydro-meteorological data involves many processes, depending on the availability and quality of data as well as the type of information under consideration, including, those listed below. Details on the analysis of these data sets are provided in the following sections.

- Rainfall data;
- Evaporation data;
- Streamflow data.

In general, it should be noted that the level of confidence that can be placed on the results of a WAA study is largely dependent on the quality of the information used, and this is particularly important in the case of hydro-meteorological data. An overarching principle should therefore be applied whereby all available data of relevance should be analysed and considered for possible use in the study. A description should always be provided of the data that has been used, supported by sound reasoning and motivations for the selection. Furthermore, a qualitative assessment must be made of the level of confidence associated with the data subsequent to the selection and analysis process. More information in this regard is provided in **Section 2**.

6.1.1 Rainfall data

Monthly rainfall time-series data provide a critical input to WAA studies and are used in the modelling of water use (particularly for irrigation and streamflow reduction processes) and water bodies, rainfall-runoff modelling as part of the surface hydrology assessment, as well as water resource system analyses.

It has been agreed that the rainfall data analysis for WAA studies would be undertaken using the *Rainfall Information Management System* (Rain-IMS) recently developed by the DWAF, Directorate: Water Resource Planning Systems. The Rain-IMS incorporates a large database of raw rainfall data, as well as the *ClassR*- and *PatchR*-utilities which were developed by DWAF for the purpose of providing a structured and scientifically sound procedure for patching rainfall data (DWAF, 1997). The Rain-IMS database consists of raw rainfall data obtained from the following sources:

- The DWAF database, which is a combination of the original DWAF rainfall database and the South African Weather Service (SAWS) database which consists of rainfall data from 1900 to September 2004;
- Data from the Water Research Commission (WRC) Project No. 1156, *The Development of an Improved Gridded Database of Annual, Monthly and Daily Rainfall* undertaken by the School of Bio-resources and Environmental Engineering (BEEH) at the University of KwaZulu-Natal (UKZN).

The process of undertaking rainfall data analyses as part of the WAA studies involves a number of main components, as summarised below. A detailed description may be found in the document *Water Availability Assessment Studies for Licensing: Hydrological Review Process* (WRP, 2006b), which is provided in **Appendix A** for reference purposes.

- Assessment of available rainfall gauge data;
- Initial screening of rainfall gauges based on length of record, quality of data, geographical location, etc., as well as the undertaking of stationarity testing by means of the so-called *single mass plot* and *cusum plot*;
- Initial screening of raw rainfall data, including the preliminary identification of monthly outlier values by means of visual inspection;
- Grouping of rainfall gauges for patching, based on:
    - Geographical location;
    - Intact years;
    - A ClassR analysis.
- Identification of monthly outlier values using ClassR;
- Determination of seasonal distribution using ClassR;
- Identification of monthly outlier values using PatchR;
- Patching of monthly rainfall data using PatchR;
- Development of monthly time-series of representative sub-catchment rainfall data;
- Undertaking stationarity testing of representative sub-catchment rainfall data.

More information on the possible sources of raw rainfall data, in addition to those available from the Rain-IMS, is provided in **Table 2-2** of **Section 2.3**.

6.1.2 Evaporation data

Evaporation data are used in WAA studies for a variety of modelling purposes, details of which are provided below. Evaporation data is generally applied in the form of 12 monthly values (for October, November, etc.) and differentiation is made between the type of evaporation data in question, as shown below.

- Rainfall-runoff modelling as part of the surface hydrology assessment (Symons-pan data);
- Irrigation and streamflow reduction processes (evapo-transpiration data);
- Modelling of water bodies in the hydrology assessment and water resource system analysis (lake evaporation data).

It has been agreed that Symons- (or S-) pan evaporation data provided in the *Surface Water Resources of South Africa, 1990* (WR90) publications for quaternary catchments would be used in WAA studies. Lake evaporation may be derived from S-pan data, by applying a set of standard S-pan-to-lake evaporation conversion factors also provided in the WR90 publications. The estimation of evapo-transpiration for particular irrigated and dry-land agricultural crops is usually undertaken by means of a simple calculation based on standard Penman-Monteith reference evaporation data and crop-specific conversion factors. More information on the possible sources of evaporation data is provided in **Table 2-2** of **Section 2.3**.

A detailed description of the evaporation data analysis may be found in the document *Water Availability Assessment Studies for Licensing: Hydrological Review Process* (WRP, 2006b), which is provided in **Appendix A** for reference purposes.

6.1.3 Streamflow data

Streamflow data provide a critical input to WAA studies and are used in the process of calibrating the rainfall-runoff model (see **Section 6.4**) and as a basis for generating natural streamflow time-series data (see **Section 6.5**) which are used as a direct input to the stochastic hydrology analysis (see **Section 6.6**) and, subsequently, the water resource system analyses (see **Section 8**).

While it is accepted that each team has its own method of developing these data sets and there should be no stipulation regarding which method to use, it is important that the results are presented in a clear and consistent manner so that they can be easily verified. The various time-series data sets used to prepare the different flow series should therefore be listed and tabulated separately.

The process of analysing streamflow data as part of the WAA studies may involve various steps, including those summarised below. A detailed description may be found in the document *Water Availability Assessment Studies for Licensing: Hydrological Review Process* (WRP, 2006b), which is provided in **Appendix A** for reference purposes.

- Assessment of available streamflow gauge data;
- Initial screening of streamflow gauges based on length of record, quality of data, geographical location, etc.
- Initial screening of raw streamflow data, including the preliminary patching of selected data values based on daily streamflow data and checking of associated rainfall events;
- Final patching of monthly streamflow data based on simulated values from the WRSM2000 rainfall-runoff model.

The primary source of raw streamflow data is recognised to be the DWAF, Directorate: Hydrology, although other sources may be considered in cases where these are available (see **Table 2-2** of **Section 2.3**).

The process of generating natural streamflow time-series data is discussed in **Section 6.5**.

6.1.4 Assessment of hydro-meteorological monitoring networks

Based on the outcome of the hydro-meteorological data analysis, conclusions and recommendations must be made related to the availability of data, including rainfall, evaporation and streamflow. Such recommendations may include aspects related to the inadequacy of existing monitoring networks, the expansion or improvement of monitoring networks and comments on the quality of observed data.

6.2 Rainfall-runoff modelling

Rainfall-runoff modelling represents the primary activity of the surface hydrology assessment and involves a process whereby the runoff response of a particular sub-catchment is simulated based on a monthly time-series of representative sub-catchment rainfall data (the generation of which is discussed in **Section 6.1.1**). Rainfall-runoff modelling will be undertaken in the WAA studies using the enhanced *Water Resources Simulation Model 2000* (WRSM2000).

WRSM2000 is based on the original model called *MORSIM* which was developed in 1973 to simulate runoff from a catchment. Later, MORSIM was enhanced and published as *HDYP09*, the model which was used in the 1981 appraisal of South Africa's water resources. A further refinement was called the *Water Resources Simulation Model 1990* (WRSM90), which formed part of the *Water Resources of South Africa 1990* (WR90) study undertaken for the Water Research Commission (WRC). Recently, the *Water Resources Simulation Model 2000* (WRSM2000) was developed, which had all the same algorithms as WRSM90 and produced identical results. This version, however, accounted for the year-2000 problem, allowed for the analysis of a record period of up to 150 years and provided interaction with the model via a graphical user interface (GUI).

For the latest version of WRSM2000 (Version 3), a number of alternative methodologies have been introduced, mainly to support the explicit modelling of water resource system components in WAA studies. Of particular significance are:

- The Irrigation Block sub-model (see **Section 4.3**);
- The new methodology for modelling streamflow reduction (SFR) areas which was developed together with Dr WV Pitman (see **Section 4.4**);
- The enhanced wetland sub-model developed by Dr WV Pitman as part of the WR2005 study (see **Section 5.3**);
- The *Groundwater-Surface Water Interaction Model* (GWSWIM) developed by K Sami (see **Section 7**).

Rainfall-runoff modelling using the enhanced WRSM2000 involves two main processes. These are the configuration and calibration of the model and are discussed in **Sections 6.3** and **6.4** respectively. Note that detailed information in this regard may be obtained from the *WRSM2000 (Enhanced) User's Guide* (SSI, 2006).

6.3 Configuration of the WRSM2000

The enhanced WRSM2000 is a modular water resources simulation program and features five different *module*-types, as listed below:

- *Runoff* module;
- *Channel reach* module;
- *Irrigation* module;
- *Reservoir* module;
- *Mining* module.

Each of these modules contains one (or offers a choice between more than one) hydrological models that simulate a particular hydrological aspect. The modules are linked to one another by means of *routes*. Multiple instances of the different modules and routes form a *network*. By choosing and linking several modules judiciously, virtually any real-world hydrological system can be represented. A short description of the network and each of these modules is provided in the remainder of this section. Detailed information in this regard may be obtained from the *WRSM2000 (Enhanced) User's Guide* (SSI, 2006).

a) Runoff module

The *runoff* module is the heart of WRSM2000 and it retains a strong similarity to what was originally known as the "Pitman model". The user should note the following:

- Pan factors are read in as data, i.e. they are not built into the program. Normally Symon's pan evaporations are used in the runoff module (see **Section 6.1.2**), but the user could adopt A-pan figures, provided suitable "crop factors" are available for natural vegetation.
- The growth of SFR and impervious areas is represented by reading in values for up to ten different years. A user defined option is available whereby the user enters the impact of the SFR area on annual (or average) flows and the impact on low flows (see **Section 4.4**).
- The module also has the facility to send fixed proportions of the total runoff along various routes. This feature enables one to economise on runoff modules in relatively homogeneous areas.
- The *Groundwater-Surface Water Interaction Model* (GWSWIM) developed by K Sami has been implemented (see **Section 7**).

b) Channel reach module

The main function of the channel reach module is to collect the inflows to it from various routes and to redistribute these flows along the outflow routes. Inflows can be in the form of predefined flows or calculated outflows from any of the five types of modules. Channel reach modules can therefore be sink modules for routes from other channel reach modules. Outflows can also be predefined flows but are more often calculated demands from adjacent modules.

The principal outflow route represents the main river channel and surplus flow is passed along this route after all demands are satisfied. The channel module also makes provision for bed losses and evaporative losses from a wetland area. This requires as input a set of twelve monthly evaporation values (see **Section 6.1.2**) and associated pan factors. A monthly time-series of representative sub-catchment rainfall data and mean annual precipitation (MAP) must also be specified so that the net evaporative losses can be computed. Additional information is also required and more information in this regard is provided in **Section 5.3**.

c) Reservoir module

The reservoir module can be used to represent a single large dam or a dummy dam (as described in **Section 5.2**). Allowance is made for the single dam to be constructed (and raised) in any year during the simulation period and for the number of small dams to change over time by inputting values of storage and surface area for up to ten different years. Evaporation is calculated based on twelve monthly evaporation values (see **Section 6.1.2**) and associated pan factors. The reservoir module collects inflows and distributes outflows in a manner similar to that described for the channel module. The one essential difference is the effect of storage, which means that the reservoir must be filled before outflow can take place along the principal outflow (i.e. spillage) route.

d) Irrigation module

The irrigation module allows for the modelling irrigation water requirements based on the Irrigation Block sub-model (see **Section 4.3**).

e) Mining module

Mining modules are used to simulate the runoff that is generated by a coal mining complex. The hydrological component of the mining module is identical to the mine sub-model that was developed for the *Water Quality and Sulphates* (WQS) model. Various components may be associated with coal mining activities and these are:

- An *o*pencast mining pit;
- An underground mine element with its underground storage dam;
- A discard / slurry dump element;
- A central pollution control dam (PCD);
- A coal beneficiation plant.

Opencast workings are further subdivided into *pre-strip*, *pit* and *rehabilitated* areas. Underground workings can be either *board-and-pillar* or *high extraction* areas. Each mining module can contain one plant area and up to 10 each of the three elements listed above. Outflow from each element may be routed directly to a river or to the central PCD via an outflow route. Certain sections may also have smaller intermediate pollution control dams that spill into the central pollution control dam.

f) Network

The main function of the network is to specify the connectivity between modules and the order in which they must be solved. In addition, the network is used to set the time period for simulation, the folders to be used for accessing input data and writing output results and to specify the routes and reservoirs that are to be reported in the model's output SUMMARY-file. The SUMMARY-file is an easy-to-check file in which monthly simulated flows in the specified routes or storages in the specified reservoirs are stored.

Finally, it should be noted that the program supports the user by means of extensive error checking and does away with the error-prone and time consuming chore of creating data files in an editor, external to the program. Where files of older versions of the program are supplied, WRSM2000 will automatically update these files to be compatible to this latest version.

6.4 Calibration of the WRSM2000

The calibration of the enhanced WRSM2000 involves an iterative process whereby adjustments are made to the *calibration parameters* that control the simulation of runoff in the sub-catchment under consideration. The objective of the adjustments is to achieve a situation where the simulated flows within a particular route in the WRSM2000 network are considered to closely mimic the historically observed flows at a streamflow gauging station, over a period for which such data are available (see **Section 6.1.3**).

The adjustment of calibration parameters is undertaken in the runoff module and the following parameters are provided (with the standard *acronym* and units, where appropriate, provided in brackets):

- Power in the soil moisture / subsurface flow equation (*POW*);
- Power in the soil moisture recharge equation (*GPOW*);
- Storage below which no recharge occurs (*HGSL*, in mm);
- Soil moisture storage capacity (*ST*, in mm);
- Subsurface flow at full soil moisture capacity (*FT*, in mm/month);
- Maximum soil moisture recharge (*HGGW*, in mm/month);
- Minimum catchment absorption rate (*ZMIN*, in mm/month);
- Maximum catchment absorption rate (*ZMAX*, in mm/month);
- Interception storage (*PI*, in mm);
- Lag of flow, excluding groundwater (*TL*);
- Coefficient on the evaporation / soil moisture equation (*R*);

In order to judge whether a calibration has been achieved, a comparison is made between the characteristics of the simulated and observed flows. The comparison is made based on a number of quantitative and qualitative observations, including:

- Statistics, such as the mean annual runoff (MAR), standard deviation (SD) and seasonal index (SI);
- The monthly hydrograph;
- The yearly hydrograph;
- The mean monthly flows;
- The gross yield curve;
- The scatter diagram;
- The histogram of monthly flows;
- The cumulative frequency plot.

More information on the calibration process is provided in the *WRSM2000 (Enhanced) User's Guide* (SSI, 2006)

6.5 Naturalisation of streamflow data

The purpose of the naturalisation process is to develop *time-series of natural streamflow data*. These sequences are representative of the streamflows that would have been generated within a particular catchment, had there been no human intervention. Natural streamflow sequences are of critical importance in WAA studies and provide analysts with stationary data (i.e. data without any intrinsic trend) that may be used as a direct input to the stochastic hydrology analysis (see **Section 6.6**) and, subsequently, the water resource system analysis (see **Section 8**).

The process proposed for developing time-series of natural streamflow data in a WAA study involves a number of steps and these are described below.

a) Step 1: Naturalisation of observed streamflows for gauged catchments

The first step in developing a time-series of natural streamflow data involves the *naturalisation* of the observed streamflow data associated with the catchment upstream of a streamflow gauging station. Naturalisation is undertaken by eliminating the impact on the observed streamflows of any human intervention that historically occurred in the catchment under consideration. This process of elimination involves either one of the following, which is undertaken on a month-by-month basis:

- The adding on of water volumes that exited the catchment, including exports, consumptive urban, industrial and irrigation water use, as well as streamflow reductions caused by commercial forestry, dry-land agriculture and alien invasive vegetation, etc.;

- The subtracting of water volumes that entered the catchment, including imports, as well as urban, industrial and irrigation return flows, etc;
- Accounting for the impact of water bodies located upstream of the gauge in question, including evaporative losses and the impact on runoff caused by the impoundment of streamflows.

b) Step 2: Extension of natural streamflows for gauged catchments

Generally, the observed data available at a streamflow gauging station does not span the full historical period of interest in a particular study. For example, while the study period may be from the 1920 to the 2004 hydrological years, observed data may only be available from 1960 to 1999. The second step, therefore, in the process of developing a time-series of natural streamflow data involves the extension of the observed naturalised data. This is achieved simply by applying the calibrated WRSM2000 rainfall-runoff model (see **Section 6.4**) and generating natural simulated streamflows for the remaining periods. In the above example, that would be for the periods 1920 to 1959 and 2000 to 2004. A time-series of natural streamflow data for the full period of 1920 to 2004 is then created by adding together the three time-series portions as follows:

- Natural simulated streamflows, for the period 1920 to 1959;
- Naturalised observed streamflows, for the period 1960 to 1999;
- Natural simulated streamflows, for the period 2000 to 2004.

c) Step 3: Scaling time-series of natural streamflows

Often the catchment area upstream of a streamflow gauging station does not correspond exactly with the sub-catchments defined for analysis purposes in the WRYM. In cases where the latter partly covers a gauged catchment, but is somewhat larger or smaller, additional manipulation is required to develop a time-series of natural streamflow data that corresponds with the WRYM sub-catchment. This is generally achieved by means of a process which involves the scaling of the gauged catchment's natural streamflow time-series data (developed through **Steps 1** and **2** described earlier). Such a scaling exercise may be undertaken in a number of ways, based, for example, on the relative catchment areas or mean annual runoffs (MARs) of the gauged and WRYM catchments.

Alternatively, natural streamflow time-series data may be developed for particular WRYM sub-catchments by adding together or subtracting, on a month-by-month basis, any number of existing catchment time-series (or portions thereof). The procedure would be directly dependent on the relative sizes and geographical locations of catchments in question. Care should, however, always be taken when subtracting time-series to avoid the generation of negative flow values.

d) Step 4: Generation of simulated natural streamflows in un-gauged catchments

In many cases, sub-catchments defined for analysis purposes in the WRYM span catchment areas where gauged streamflow data are not available, either because the data are considered to be unusable, or no flow gauging structure exists. In these cases, time-series of natural streamflow data, spanning the full historical period of interest, are simply generated using the WRSM2000 model. However, since gauged flow data are not available, and, hence, no calibration of the WRSM2000 model is possible (see **Section 6.4**), the WRSM2000 simulation must be undertaken based on calibration parameters obtained from elsewhere. Typical sources include:

- Parameters derived by means of the WRSM2000 calibration of a nearby catchment considered to have similar hydrological response characteristics;
- Regionalised parameters from publications such as the *Water Resources of South Africa, 1990* (WR90).

6.6 Stochastic hydrology analysis

The process of undertaking stochastic yield analyses is described in **Section 8.3.2** and involves the analysis of water resource systems based on natural streamflow sequences that were generated synthetically. The main result of a stochastic system analysis includes the assurances of supply (or, inversely, the risk of failure) for imposed target drafts. Stochastic streamflow sequences are generated by the WRYM at runtime, a process which is based on the application of appropriate statistical distribution models and parameters for the generation of synthetic streamflow sequences. The statistical distribution models and parameters are derived by means of stochastic hydrology analysis, details of which are provided here.

The basic input to the stochastic hydrology analysis is time-series of historical natural streamflow data (see **Section 6.5**) and may be undertaken using the *Monthly Multi-Site Stochastic Streamflow Model* (STOMSA). The model was developed as a user-friendly application with the primary objective of generating stochastic streamflow sequences. It is designed to perform the whole range of procedures involved with a standard stochastic streamflow analysis, including the following:

- Selection of the appropriate statistical distribution model;
- Statistical model parameter estimation;
- Stochastic streamflow generation;

- Verification and validation to test the validity of generated stochastic streamflow sequences.

A detailed description of the fundamentals of stochastic streamflow generation may be found in the *STOMSA User Guide* (WRC, 2003), together with the following information:

- Background to the development of the model;
- Details on model data requirements;
- A step-wise description and guide to the use of the model features;
- An example of a model input data set and related output information.

7. GROUNDWATER-SURFACE WATER INTERACTION

The *Groundwater-Surface Water Interaction Model* (GWSWIM) methodology will be applied in WAA studies for the explicit modelling of the interaction between groundwater and surface water resources and, therefore, the impact of groundwater abstractions on surface water flows. The methodology was recently developed by K Sami and has been incorporated as a sub-model into the enhanced WRSM2000 model, for use in the hydrological calibration and naturalisation processes. At the time when the initial five WAA studies were undertaken (as discussed in **Section 1**), implementation of GWSWIM in the WRYM had not yet been completed. On completion, however, similar modelling will be possible in the yield assessment process.

The logical stepped methodology utilises a time-series of the Pitman *S* variable (subsurface storage) from WRSM2000 as input data, from which a time-series of recharge is generated. This approach provides a direct link to the Pitman model. Interflow and groundwater base flow are derived independently and used to simulate base flow to the catchment hydrograph..

The methodology is based on:

- Utilising the catchment total soil moisture (or S) time-series generated by WRSM2000 to calculate a time-series of recharge;
- Incrementing a percolating storage by recharge, with any recharge in excess of percolating storage capacity being dumped to aquifer storage;
- Calculating interflow from the percolating storage utilising the Pitman methodology;
- Incrementing groundwater storage from the percolating storage up to a maximum recharge rate, with any recharge in excess of the maximum recharge rate contributing to interflow;
- Depleting groundwater storage by evapo-transpiration and groundwater outflow to other catchments as a function of groundwater storage until static water level conditions are reached;
- Calculating groundwater base flow or transmission losses in a non-linear manner as a function of groundwater storage and runoff volume;
- Depleting groundwater storage and groundwater base flow due to abstraction as a function of aquifer diffusivity, time since pumping started, distance, and recharge

A detailed description of the *Groundwater-Surface Water Interaction Model* (Sami, 2006b) is provided in **Appendix C**.

8. WATER RESOURCES SYSTEM ANALYSIS

Water resource system analyses will be undertaken in the WAA studies using the *Water Resources Yield Model* (WRYM). The WRYM was developed by the South African Department of Water Affairs and Forestry (DWAF), for the purpose of modelling complex water resource systems. It is used together with other simulation models, pre-processors and utilities for the purpose of planning and operating the country's water resources. Recently, the *Water Resources Yield Model Information Management System* (WRYM-IMS) was developed to improve the performance and ease of use of the model by providing a database to manage WRYM data sets, as well as an interface which allows for system configuration and run result interpretation through a graphical user interface (GUI).

Information on the configuration and testing of the WRYM, as well as the undertaking of system analyses and the assessment of water availability for water resource systems is provided in the remainder of this section.

8.1 Configuration of the WRYM

8.1.1 General

In **Section 3**, an overview is provided of the process to develop a representative system network model, which involves the identification of the main physical features of the water resource system under consideration and the lumping of system components according to the required modelling resolution. The result is a schematic diagram which indicates the connectivity between and nature of the various components that make up the system in question.

Based on this definition, the WRYM may be configured using the model's *basic building blocks*. These basic building blocks, which are generic in nature, are used to represent specific system components and include *channels* and *nodes*. A brief description of the purpose and creation of each in the WRYM is provided in the remainder of this section. Greater detail is available from the *WRYM User Guide* (DWAF, 1999) and *WRYM Procedural Manual* (DWAF, 2005a).

a) Channels

Channels represent conduits that convey water between nodes within a water resource system network and are used to model a variety of functional system features such as river reaches, canals, pipelines, hydraulic structures as well as defined water requirements imposed on the system. In selecting channels for the system network definition, care should be taken to include all constraints that could have an impact on the yield of the system or dictate the system operating rules.

Creating channels

Channels are created in the WRYM-IMS by following a standard procedure involving four steps. These are discussed below:

- **Step 1**: An instruction must be given by the user to *create a new channel* and subsequently the definition of the locality and flow direction of the channel by specifying the associated upstream (tail) and downstream (head) nodes. It should be noted that, when a new channel is created in the WRYM-IMS, the model will automatically assign an appropriate channel number and the channel will always be of the one-arc general flow channel-type. These channels represent open river reaches with no capacity constraint and are considered in the WRYM-IMS to be channels without an associated functional system feature.

- **Step 2**: The user must specify the *name* of the new channel, which will be displayed by the WRYM-IMS in the tree-view navigation screen.

- **Step 3**: An appropriate *penalty structure type* is defined. Penalty structures are defined prior to the creation of new channels and are structured using the basic building blocks of channels called *arcs*. More information on arcs is provided later in this section.

- **Step 4**: A *functional system feature* is defined, which determines the specific function that the channel will fulfil within the context of the system. The functional system feature selected will, in turn, determine the channel type which is used by the WRYM for modelling the channel within the system's network definition.

Channel types

The WRYM allows for twelve different channel types, each of which is used to model a particular functional feature that may occur in a water resource system network. A brief functional description of the most important channel types is provided below:

- *Master control channel*: There are two types of master control channels. The first is a water master control channel used to determine the water resource supply capability (yield) of a system. The second is a power master control channel for determining the hydropower generating potential of a system.

- *General flow channel*: This channel is generally used to simulate flow in a river reach that does not have a capacity constraint or upper limit.
- *Multi-purpose min-max channel*: This is a versatile channel type which can be applied for a variety of functions, including the modelling of abstractions with multiple-level curtailment requirements, as well as the incorporation of physical flow constraints of different kinds into the network model;
- *Loss channel*: Loss channels simulate flow-related losses. Losses are based on a percentage of the flow in the main channel or through a user-defined relationship.
- *Diversion channel*: This channel is used to model the efficiency of diversion structures to utilise runoff from an unregulated river reach, within the context of the monthly time-step used by the WRYM. More information regarding the configuration of diversion channels is provided in **Section 8.1.3**.
- *IFR channel*: This channel can be used to model ecological water requirements, in the form of an in-stream flow requirement (IFR), based on a user-defined relationship with runoff into the water resource system network.

Channel arcs

The basic building blocks of channels used in the WRYM are called arcs. Arcs allow for channels to be configured in such a way that particular flows are allowed through them under specific circumstances. This is achieved by defining, for each arc, three data values:

- A lower flow limit;
- An upper flow limit, that can not be exceeded under any circumstances;
- A penalty associated with each unit of flow through the arc. Penalties are used in the WRYM as a simple tool that enables the user to define selected operating rules in a water resource system. More information in this regard is provided in **Section 8.1.2**.

Although the use of up to five arcs per channel is allowed by the model, one and two-arc channels are generally sufficient to model most situations encountered in water resource system networks and these are discussed below.

- *One-arc channel*: This is the simplest type of channel and is modelled using one arc, with the lower limit equal to zero and the upper limit set to the capacity of the system component that the channel represents.
- *Two-arc channels*: These channels are generally used to draw (pull) a target flow from one part of the system to another, typically for the purpose of modelling imposed drafts and water requirements, inflows to the system, controlled releases from reservoirs, streamflow diversions and flow-related losses. Target flows are defined for different channel types in different ways. For example, in the case of master control and multi-

purpose min-max channels monthly target flows are defined by the user. For all other channels, such as IFR and loss channels, the target flow for a specific month is calculated by the model at run-time based on various user-defined relationships.

Channel penalty structures

Channel penalty structures are defined in terms of the characteristics of channel arcs, including the number of arcs used to model a channel and the penalty associated with every unit of flow in the arc. For this purpose a variety of standard channel penalty structure types are defined and the appropriate type assigned to each channel in the system. This approach allows for the utilisation of a particular penalty structure type in the definition of more than one channel. More information on penalties is provided in **Section 8.1.2**.

b) Nodes

Nodes serve primarily as junctions within a water resources system network and are used to join channels according to the physical layout of the network. In many cases, nodes also perform special functions within the system context, including the modelling of reservoirs, which have the capability of retaining water over time, as well as points at which inflows from incremental sub-catchment runoff enter the system network. Node types are discussed below.

Junction nodes

Junction nodes have the exclusive function of joining channels according to the physical layout of the water resource system network, which includes:

- Combining the flow from tributary catchments;
- Representing points from where water can be abstracted or diverted, while taking account of the appropriate locality and associated resource availability for a particular water user within the system context;
- Providing the capability of splitting conveyance routes to simulate physical constraints that may differ along a conduit;
- A special node type, referred to as the *zero-node*, is also used and represents an imaginary point outside of the system being modelled. The zero-node is used as a downstream point (head) for channels that model flows leaving the system (e.g. consumptive water uses, losses, etc.) or as an upstream point (tail) for channels that model flows entering the system from elsewhere (e.g. return flows, inflows from other systems, etc.).

Reservoir nodes

Reservoirs have the capability of retaining water over time and are modelled in the WRYM using of a special reservoir node-type. Reservoir nodes are defined by means of a number of variables relating to the following:

- *Physical characteristics*: This includes a unique name, a status indicator which is used to define whether a reservoir exists or nor, the full supply level (FSL), dead storage level (DSL) and bottom level (which signifies zero storage), a defined relationship between elevation, storage capacity and surface area, the water level in the reservoir at the start of the analysis and monthly lake evaporation values.
- *Storage zones*: A reservoir can be split into different storage zones for the purpose of controlling the way in which it is drawn down. In general, the first zone in a reservoir lies above the full supply level (FSL), while the last zone is defined by the dead storage level (DSL) and bottom level. The remaining zones are defined by specifying the elevation of each lower zone boundary.
- *Penalty structures*: Penalty structures are defined in terms of storage zones, rule curve levels and zone penalties. Penalties are assigned to a particular zone in a reservoir in order to signify the *dis-benefit* or *benefit* associated with having water in storage while the storage volume in the reservoir falls within the zone in question. Penalties are used in the WRYM as a simple tool that enables the user to control the way in which a reservoir is operated. More information in this regard is provided in **Section 8.1.2**.
- *Rule curve*: Most reservoirs in a water resource system are operated with storage zones from which water is abstracted to supply water users. Certain reservoirs, however, may be operated with a flood attenuation zone, which is a zone reserved for flood events and, ideally, should be kept empty. The level between such zones may be referred to as the ideal level and is defined in the WRYM by the rule curve.

8.1.2 System operating rules

System operating rules are defined in water resource systems to address aspects like the supply priority amongst water users, prioritisation of the use of water sources, inter-reservoir and inter-basin support rules, as well as reservoir operational levels and drawdown rules. The selection of operating rules is of great importance because they have a direct impact on the capability, assurance and sustainability of a system's water resources, as well as the financial costs associated with its operation.

The standard procedure for developing operating rules involves a number of steps, which represents an iterative process that can be repeated as many times as required. Note that typically the objective when following this procedure is to achieve the maximum system yield while minimising or limiting the associated operational costs.

- Selection of an initial set of operating rules based on chosen objectives with regard to the behaviour of the system. This step is probably the most difficult and relies greatly on the intuition and experience of the water resource system analyst.
- Implementation of the selected operating rules in the network model and undertaking of a model run.
- Evaluation of the level of achievement of selected objectives based on the behaviour of the system as exhibited in the simulation results.
- Usually, selection of an alternative set of operating rules followed by repetition of the above steps.

The operating rules selected for a water resource system network model is implemented in the WRYM-IMS based on a mechanism called *penalties*. Penalties are dimensionless values assigned by the modeller and are used by the WRYM as the basis for flow routing solutions. This is achieved by comparing the overall dis-benefit of one flow routing option with that of another, with the objective of minimising the overall dis-benefit which is incurred.

In the case of channel routes, a penalty is assigning to every unit of flow through each channel arc. Penalties are also assigned to every unit of water impounded in reservoirs. These reservoir penalties represent a benefit (or in some cases dis-benefit) of having that unit of water available in the reservoir in question. The model interprets the reservoir penalty by comparing the benefit of having water in one reservoir with the benefit of having it in another, while also considering the dis-benefit that might be incurred if the water is transported or if certain water users in the system are not supplied.

More information in this regard provided in the *WRYM User Guide* (DWAF, 2008) and *WRYM Procedural Manual* (DWAF, 2005a).

8.1.3 Flow diversions from unregulated river reaches

The modelling of flow diversions from unregulated river reaches will be required in WAA studies as part of the yield assessment process. For this purpose, the existing WRYM diversion channel feature will be used which allows for diversion structures, and their efficiency to utilise unregulated flow, to be modelled within the context of the monthly time-step used by the WRYM. For each diversion channel, a data table is populated, which defines either one of the following:

- A relationship between monthly natural runoff reference flows (into the upstream system node) and the corresponding diversion flows;
- A relationship between monthly reference flows (into the upstream system node), including both natural runoff and upstream inflows, and the corresponding diversion flows.

It should be noted that a tool has recently been developed by the DWAF, Directorate: Water Resource Planning Systems to facilitate the analysis required for determining flow diversion efficiency characteristics based on daily streamflow data. The tool produces:

- A set of monthly reference flow values;
- A set of corresponding diversion flows;
- A set of data pairs that define the reference flow-vs.-diversion flow relationship to populate the WRYM parameters related to the configuration of diversion channels in the WRYM.

A detailed description of the methodology for modelling diversion channels in the WRYM and WRYM-IMS, as well as information regarding the tool proposed for facilitating its configuration (as mentioned previously), is provided in the supporting document *Detailed Business Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2006a).

8.2 Testing the WRYM network configuration

As part of the process of configuring the WRYM (discussed in **Section 8.1**) it is the responsibility of users always to verify and test that the basic input information and the related system network definition provided are correct and accurately represent the intended configuration. Extreme discipline should be employed in this regard as users ultimately carry the responsibility for model results.

The newly developed *Water Resources Yield Model Information Management System* (WRYM-IMS) provides the user with numerous automated model verification and testing features that assist in avoiding mistakes during the process of configuring system networks. The most important of these is the *Validate model data*-feature, which is activated by the user and outputs a detailed validation report, including a list of warnings and errors related to problems identified. This provides the user with the opportunity of addressing problems before attempting a model run. However, automated checks are, by nature, limited and it is recommended that, once model users have modified a system configuration and utilised the

WRYM-IMS validation feature, additional verification and testing procedures be followed to check its correctness and impact on the system's behaviour.

Generally, a standard procedure is followed when implementing system model configuration changes whereby each modification is implemented and then verified and tested individually. Such a procedure would involve a number of steps as outlined below. It should be noted, however, that while this procedure should generally be sufficient for application under most circumstances, model users should follow their discretion in this regard and undertake more exhaustive tests in cases where it is considered to be warranted. Although this approach might seem cumbersome, it is often of great value as it insures that the required modelling results are achieved at all times. It should be followed whenever possible, especially by inexperienced model users.

- **Step 1**: Document the nature and purpose of the required modification;
- **Step 2**: Implement the modification following standard procedures;
- **Step 3**: Verify the system network integrity;
- **Step 4**: Test the system operational behaviour;
- **Step 5**: If required, correct the implemented modification and repeat the procedure.

More detailed information on the above steps may be found in the *WRYM Procedural Manual* (DWAF, 2005a).

8.3 Undertaking WRYM system analyses

Traditionally, the purpose of undertaking system analyses with the *Water Resources Yield Model* (WRYM) was to determine, at a particular point in a water resource system, the resource capability of the system, given a particular system configuration and operational regime. The resource capability is expressed as a *system yield*, which is an annual volume either supplied on a firm basis (i.e. no supply failures occurred) or supplied at a given reliability, in both cases based on the results of the analysis undertaken.

Such an analysis is undertaken by imposing on the system, at the point of interest, target water requirements or (*target drafts*) via a special WRYM channel type referred to as the *master control (or yield) channel*. By analysing the ability of the system to supply water for the imposed target draft, the system yield and related characteristics (i.e. reliability) could be determined. Such analyses may be either *historical* or *stochastic* and more information in this regard is provided in the following sections.

It should be noted, however, that within the context of the WAA studies the need arose to produce results such as those traditionally available for the yield channel (i.e. summarised supply characteristics) for all water users modelled in the system. For this purpose, a suite of results display features have been developed and implemented in the *Water Resources Yield Model Information Management System* (WRYM-IMS). More information in this regard is available in **Section 10.2.1**. In principle, this implies that any modelled water user may effectively be treated like a yield channel.

8.3.1 Historical analyses

A historical system analysis is undertaken the network model is simply analysed using the historical natural streamflow, diffuse requirement and streamflow reduction sequences contained in the monthly hydrological time-series data files (one set of *.INC, *.RAN, *.IRR and *.AFF for each incremental catchment modelled in the system). The main results of a historical system analysis include the historical firm yield of the system (the determination of which is described below) and the historical supply characteristics to modelled water users. It should be noted, however, that based on a historical analysis alone, the results would not provide an indication of the reliability of supply associated with the system yield.

The historical firm yield of a system is determined by means of an iterative process, where the system is analysed with a range of target drafts imposed on the yield channel. The results are displayed in a WRYM-IMS table of target draft and yield (both in units of million m^3/a). The firm yield is generally taken to be the maximum target draft that can be imposed without causing the system to fail. The WRYM-IMS also provides a feature whereby the interactive input from the user is reduced by allowing the model automatically determine the historical firm yield of a system by means of an automated search routine. For this purpose, the user must define two target drafts, an upper value and a lower value, between which the firm yield is expected to occur.

8.3.2 Stochastic analyses

A stochastic yield analysis is undertaken based on natural streamflow sequences generated stochastically, as well as appropriate monthly target flows for diffuse water requirements and streamflow reductions. The latter is achieved by means of methodology which involves the selection of data values from the historical data files (*.IRR and *.AFF), based on the relationship between the historical and the stochastically generated annual flow values for the year in question. Stochastic sequences are generated by the WRYM at runtime, a process which is based on statistical parameters derived from a stochastic hydrology analysis as discussed in **Section 6.6**.

Stochastic analyses are sometimes undertaken on a single stochastic sequence, in which case the results may be interpreted in a similar way as those for historical analyses as described in **Section 8.3.1**. Mostly, however, multi-sequence stochastic analyses are undertaken, which means that the system is analysed multiple times, each time based on a new set of stochastically generated hydrological sequences of natural runoff time-series.

The main results of a stochastic system analysis include the assurances of supply for imposed target drafts (the determination of which is described below) and the assurance of supply characteristics to modelled water users.

The reliability of supply associated with a particular target draft is determined by the model based on the number of analysed sequences for which failures were simulated. The assessment of the reliability characteristics of a system is generally based on the analysis of a range of target drafts. As for historical analyses, the model also provides a feature to automatically determine the stochastic yield of a system at a selected recurrence interval (RI) of failure, by means of an automated search routine. For this purpose, the user must define two target draft values, one with a RI expected to be lower and the other higher than the specified RI.

The yield channel results of a stochastic analysis are displayed in a WRYM-IMS table showing target drafts (in units of million m^3/a), together with the associated reliability of supply (as a %) and RI (in years). The results may also be displayed graphically using the WRYM-IMS *Yield Reliability Curve* (YRC) -feature to plot a standard yield-reliability graph.

When a stochastic analysis is undertaken, the user may further customise the analysis by selecting from a number of stochastic run options. These relate to aspects such as the sequences to analyse, the type of stochastic streamflow generation, the automatic determination of stochastic yields, as well as further options for short-term stochastic analyses and are discussed in greater detail in the *WRYM Procedural Manual* (DWAF, 2005a).

8.4 Assessment of water availability

8.4.1 Overview

Assessing the water availability at local catchment level will require simulating how an abstraction is supplied based on analysis of the historical and/or stochastic hydrology. Statistical and graphical presentations of the supply results will be compiled and compared against the reliability of supply criteria. The level of compliance or violation will also be reflected in order to provide information on how large the over-abstraction is or give an indication of what the extent of the excess could be. Various analyses will be carried out where different water abstraction volumes are imposed on the system and analysed as scenarios. As an example, one scenario could be to impose all the current water use onto the system and another to impose only the lawful water entitlement volumes on the system.

8.4.2 Water supply compliance criteria

The compliance criteria will be defined in the form of a priority classification and reliability definition table. An example of such a definition is presented in **Table 8-1**, showing how a water abstraction is portioned into priority classes and what reliability (allowed risk of supply failure) is assigned to each priority class. The table also presents an example of how users could be distributed between the priority classes. Irrigation, which can handle a lower assurance of supply has allocated 30% of the total irrigation into the low priority class, and 10% to the high priority class. Mining and Industries have allocated 80% of their demand to the high priority class as the industry requires water at a high assurance of supply. This is merely an example and could differ between water management areas.

Table 8-1: Example priority classification and reliability criteria definition

Description	Priority classes and percentage of user group demand			
Priority category name	Low	Medium Low	Medium High	High
Assurance of supply	90 %	95 %	98 %	99.5 %
Risk of supply failure	10 %	5 %	2 %	0.5 %
Recurrence interval of supply failure	1:10 years	1:20 years	1:50 years	1:200 years
Typical user groups (% of demand)				
Irrigation	30 %	30 %	30 %	10 %
Domestic	5 %	15 %	30 %	50 %
Mining / industrial	5 %	5 %	10 %	80 %

The intention is that the parameters of the priority classification and reliability criteria will be selected through workshops with the water users. It is envisaged that scenarios of different parameter settings be analysed and the results presented at the workshop to illustrate to the water users the implications of a range of parameter values. The aim with this method is to allow the water user to interpret the water supply results in context of their respective tolerances for risk and be able to selection appropriate reliability of supply criteria.

8.4.3 Assessing assurance of supply

The principle that will be followed in assessing how the system is able to supply (satisfy) the reliability criteria is to simulate the water resource system and evaluate the supply result for occurrences of failures in the supply. Statistical and graphical analysis of the supply results will be carried out and compared against the reliability criteria to determine whether the supply complied with the criteria.

These simulations (system analyses) will be undertaken based on historical as well as stochastic hydrological sequences. The historical analysis will provide a reference to “known” wet and dry periods and thereby demonstrate how the scenario would have performed during historical events. The stochastic analyses serve as the rigorous assessment method of the assurance of supply.

An essential element of assessing the assurance of supply is how a failure in supply is interpreted or what the definition of a failure is. The most stringent definition (which is currently applied in the yield analysis methodology) is that any failure to supply a given volume of abstraction (even if the failure is very small) constitute a non-supply event and is “flagged” as such in the statistical evaluation of the simulated results. Although this stringent definition of a failure is applicable for high priority and essential water uses, other more “lenient” definitions could be investigated for water uses such as run-of-river irrigation of low value crops.

8.4.4 Undertaking scenario analyses for water allocation

A key component of the analysis procedure to determine the water availability will involve simulating various scenarios. A scenario will consist of a particular set of settings or parameter values that could represent a plausible allocation configuration. The results of the scenarios will be interpreted for compliance and failure to comply will lead to adjustments to the original scenario parameters and the formulation of further scenarios.

Scenario analysis and the evaluations (comparison) of their results provide a valuable means of creating an understanding to the "behaviour" of the water resource system. Interdependencies will be identified and problem areas (areas of over-allocation) highlighted through the evaluation of the results of various scenarios.

Since the overarching objective of the WAA studies is to provide technical information for the process of eventually establishing an allocation schedule, it will be required to analyse various scenarios of water abstraction volume settings which will inform the decision (selection) of the allocation schedule.

Typical scenarios would include the following:

- Assessing the consequences of different ecological management classes (EMCs) on the water available for allocation;
- Determine the assurance of supply based on the current water use in the system;
- Evaluate the assurance of supply for the situation where all the lawful water use entitlements are being exercised;
- Through the process of analysing scenarios iteratively determine the maximum allowed allocation at various nodes (locations) in the water resource system.

8.4.5 Preparation of information for results presentation

A key to the evaluations of compliance, as discussed in the pervious sections, is the ability to produce (post-process) the statistics and graphical presentations automatically and rapidly from the simulation results. To this end, numerous result presentation features are currently being implemented into the WRYM-IMS including tabulated and various graphically displays.

One of the objectives with the result presentation features is that scenario analyses and compliance evaluations should be possible in a workshop environment. Due to the time limitations in a workshop it would not be possible to carry out a full stochastic analysis of, say, 201 stochastic sequences. In this instance the analysts will have to prepare scenarios prior to the workshop based on the full stochastic analysis. This will then serve as a guide to interpret selected sequence analyses.

9. WATER QUALITY ASSESSMENT

9.1 Aim of the water quality assessment

The aim of the water quality assessment in the WAA studies is to assess the impact on water quality of the water allocation plan. The water allocation plan is directly linked to the water quality of a Water Management Area (WMA). The factors that will typically be addressed by a water allocation plan that could affect water quality are:

- Abstractions and water transfers out of a WMA;
- Reconciliation strategies which could include the construction of dams and operating rules;
- Streamflow reduction activities such as commercial forestry;
- Land use changes such as urbanisation and agriculture;
- Irrigation;
- Mining;
- Return flows from mines, industries and sewage treatment plants. The impact of water conservation and demand management on the quality and quantity of return flows should also be considered.

A degree of understanding of the water quality in the river system has to be developed which will allow for at least a qualitative assessment to be made of the effect that changes in the factors listed above could have on the water quality of the river system. Ideally a water quality model for the study area should be used for the assessment. However generally a model will not be available for the study area and the scope of work will not provide for the setting up and calibration of a model.

9.2 Baseline information requirements

The baseline information needed to develop a reasonable level of understanding of the water quality aspects of the river system includes:

- A map showing the location of irrigation areas, agriculture, commercial forestry, urban areas, mines, industries, point discharges, catchment boundaries, major dams, abstractions and the major streams. This map would largely be developed as part of the hydrological assessments or in the development of the schematic for the WRYM.

- Water quality data collected in the catchment. The data should be recent and should cover the last 5 to 10 years. The source of this information is the Department of Water Affairs and Forestry databases both in the regional offices and at the Institute of Water Quality Studies (IWQS). Local authorities and water boards can also assist with the provision of data.
- Water quality data of the point discharges. These discharges are generally licensed and water quality and quantity information related to the discharge have to be provided to the Department's regional office. The Regional office and the discharger can be approached for this information.
- Water quality requirements which may have been set as part of an Ecological Reserve determination.
- Resource Water Quality Objectives (RWQOs) for the river system. The RWQOs may already have been set by the Department in consultation with the water users in the WMA or as part of the ecological Reserve determination. The RWQOs are based on water user requirements for water quality. The South African Water Quality guidelines are used to provide the requirements for the different users. These guidelines have been captured in a "Dashboard" tool which can be used to assist with the setting of RWQOs.
- The major water users in the catchment. For water quality purposes these would be grouped into the users as per the water quality guidelines, i.e. Domestic, irrigation, stock watering, industry, aquatic and recreation. The hydrological study and water demand data would assist with the collection of this data.
- Changes to discharge volumes and qualities should be determined especially if water conservation and demand management is to be implemented.

In many areas a water quality situation assessment may have been undertaken. If the assessment is recent much of the information required will be readily available. There may also be a water quality model set up for the catchment. This will most likely be the WQT model which models TDS. This model, if recently calibrated will provide the basis for the water quality assessment of the allocation plan.

9.3 Assessing water quality characteristics

The purpose of this part of the assessment is to process the baseline data and information to gain an understanding of the water quality being seen in the river system and to relate this water quality to the sources of pollution. This understanding will be the basis for the assessment of the impact of the water allocation plan. To develop the required understanding the following should be undertaken:

- The water quality data of the rivers, dams and the discharges should be assessed by looking for trends, seasonality and carrying out basic statistics (production of percentiles). Plots of the water quality data can be used to identify the trends. Box and whisker plots of the water quality data collected in each month can be used to show the seasonal behaviour of water quality.
- If RWQOs have not been set then the location of the water users in the catchment and the water quality guidelines should be used to set RWQOs.
- The results of the statistical analysis of the data should be compared to the RWQOs so that the water quality variables of concern can be identified.
- The results of the water quality data assessment should be used together with the map showing the land-use and the locations of the water users, water infrastructure, catchment boundaries, point source discharges and the water quality monitoring points, to divide the major rivers in the catchment into river reaches. The concentrations of the water quality variables of concern in each of these reaches should be characterised as far as possible using the available data.
- The river reaches where the water quality is good, marginal and unsatisfactory should be identified.
- The causes of the concentrations seen in the river reaches should be identified. The causes could be contributions from a tributary, point source discharge or diffuse pollution.

9.4 Assessing impacts of implementing water allocation plan

If a water quality model exists, the model can be updated to represent the proposed water allocation plan. The model can then be applied and used to assess the impact for the water quality variable modelled. The extent of the change can be used to assess other water quality variables which may be an issue.

If a water quality model is not available, the assessment will be qualitative. The assessment involves the use of the understanding that has been developed to assess if the water allocation plan will significantly impact on water quality. The change in flow rates in the different river reaches needs to be determined and compared to the base case which represents the current water quality situation in the rivers. Increases or decreases and the magnitude of the change in the flows in the river reaches and impoundments and the sources of the flow changes can be used to determine the changes that can be expected in the water quality in the different reaches.

A rating system can be developed. The rating could be expected improvement in water quality, no change expected, deterioration but not exceeding the RWQOs or deterioration exceeding the RWQOs. The water quality assessment can then be used to revise the water allocation plan. If however a qualitative assessment cannot be made with high confidence, then consideration should be given to the application and calibration of a water quality model.

10. COMMUNICATION AND INFORMATION STORAGE

10.1 Stakeholder communication

Although the WAA studies focus on technical assessments of the water resource, stakeholder communication and involvement in the formulation of the models is essential. The intention is that the WAA studies will have to provide results for stakeholder meetings, however, the stakeholder engagement process will be managed and facilitated by the Directorate: Water Allocation Reform as part of the process to license water use.

There are however specific requirements for stakeholder communication from the WAA studies which include the following:

- Obtain agreement with the stakeholders on the formulation of the systems network model;
- Provide capacity building (training) initiatives to inform the stakeholders of the analysis methodology that will be applied;
- Interact with the stakeholders to define the priority classification and reliability criteria parameters;
- Present scenario results to the stakeholders and define alternative scenarios based on their requirements and needs.

10.2 Documentation

10.2.1 Reporting on methodologies, assumptions and results

Reporting provides the primary means of communication from those that undertaken WAA studies to other WAA studies, the Client, stakeholders and other interested parties (see **Section 10.1**). It is therefore paramount that reporting is undertaken in such a way that sufficient descriptions are provided on all aspects related to the study in question.

As discussed in **Section 1.2**, one of the main aims of the five WAA studies is to develop modelling approaches and procedures that can be used for decision support in the compulsory licensing process and it is therefore critical that the methodologies applied can withstand public, technical and legal scrutiny. Reporting in a WAA study on the methodologies that have been applied must therefore be as comprehensive as possible and care should be taken to provide the appropriate motivation in cases where these methodologies deviate from those presented in this document.

In support of the five WAA studies, a detailed assessment was undertaken by the DWAF Directorate: Water Resource Planning Systems of the WRYM and WRYM-IMS functionalities that would be required in order to provide effective communication to stakeholders on the assumptions applied and results obtained from the water resource system analysis process. It is of great importance that reporting in a WAA study be undertaken in such a way that it provides comprehensive information in this regard and that, for this purpose, the available functionalities be applied. These include:

- Displaying assurance of supply and monthly supply patterns;
- Displaying compliance with water user assurance criteria;
- Displaying duration and frequency of deficits;
- Displaying the surplus allocable amount;
- Aggregation of results to provide a summarised view of the water supply situation in a system;
- Illustrating modelled operating rules and compliance with actual implemented rules;
- Illustrating the simulated behaviour of a system under familiar historical events;
- Providing information on a particular water requirement channel defined in the model, e.g. the water user classification or a list of the water users associated with the channel in question;
- Displaying WRYM networks on a GIS background, allowing for users to activate any of the above features by clicking on the appropriate system component.

More information in this regard may be found in the document *Detailed Business Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (WRP, 2006a).

10.2.2 Set of reports required

It is proposed that the reports compiled as deliverables from a WAA study include the following, as appropriate:

- Study inception report;
- Rainfall data analysis;
- Streamflow data analysis;
- Surface hydrology assessment;
- Groundwater hydrology assessment;
- Water quality assessment;
- Water resource system analysis;

- Main Study report.

10.2.3 Reporting standards

It is accepted that group undertaking a WAA study would follow its own reporting standards and that there should be no rigid stipulation in this regard. It is, however, important that the reporting is done in a clear and consistent manner so that they can be used effectively as a means of communication. It is therefore proposed that all WAA study document should follow a standard structure which includes the following components, as appropriate:

- A *fly-sheet* providing details on the report as well as the approval of the document by the professional service provider and the client. An example may be seen at the beginning of this document.
- An *executive summary*. Note that this section should always be kept concise and should contain only information on the main methodologies applied, assumptions and results;
- A table of contents showing all sections down to the third level, with associated page numbers.
- A list of abbreviations;
- A list of tables;
- A list of figures;
- An introduction section which may include background, as well as information on the purpose and structure of the document.
- The main body of the report which may contain many sections providing detailed information on methodologies applied, assumptions and results.
- Sections containing conclusions and recommendations.
- A list of all references.
- Appendices including supporting information. This must include an appendix detailing data and information provided with the document in electronic format. Reference may be made to hydro-meteorological data, model configuration data and results information and documentation. Details on such an information repository are provided in **Section 10.3**.

10.3 Information repository

Details are provided below on the structure of information repositories to be provided with a WAA study, including the appropriate data file name conventions, data directory structures and model databases for the hydrological and water resource system analyses.

Table 10-1: Information repository for hydrological analyses

Directory name and location / information description	Units	File name structure		Example
		Name	Extension	
1. Documentation				
1.1 Study Documentation				
Study report	N/A	DWAF report No.	PDF	PWMA1/A42/1207.pdf
1.2 Supporting Documentation				
Various documents, as appropriate	N/A	Reference	PDF	DWAF (2005).DOC
2. Water Use and Return Flows				
2.1 Irrigation				
Time-series of modelled historical monthly irrigation water requirements, supplied from dummy dams	million m^3	Catchment No. + HIS	IDR	A42A1HIS.IDR
Time-series of modelled historical monthly irrigation water supply, from dummy dams	million m^3	Catchment No. + HIS	IDS	A42A1HIS.IDS
Time-series of modelled historical monthly return flows from dummy dam irrigation	million m^3	Catchment No. + HIS	IDF	A42A1HIS.IDF
Time-series of modelled historical monthly irrigation water requirements, supplied from run-of-river schemes	million m^3	Catchment No. + HIS	IRR	A42A1HIS.IRR
Time-series of modelled historical monthly irrigation water supply, from run-of-river schemes	million m^3	Catchment No. + HIS	IRS	A42A1HIS.IRS
Time-series of modelled historical monthly return flows from run-of-river irrigation	million m^3	Catchment No. + HIS	IRF	A42A1HIS.IRF
Time-series of modelled historical monthly irrigation water requirements, supplied from groundwater	million m^3	Catchment No. + HIS	IGR	A42A1HIS.IRR
Time-series of modelled historical monthly irrigation water supply, from groundwater	million m^3	Catchment No. + HIS	IGS	A42A1HIS.IRS
Time-series of modelled historical monthly return flows from groundwater	million m^3	Catchment No. + HIS	IGF	A42A1HIS.IRF
2.2 Other				
Time-series of monthly water requirements	million m^3	Name + HIS	REQ	Eshowe.REQ
Time-series of monthly return flows	million m^3	Name + HIS	RF	Eshowe.RF
3. Hydro-meteorological Data				
3.1 Rainfall				
3.1.1 Raw				
Time-series of monthly raw rainfall data	mm/10	Gauge No.	RAW	0588573.RAW
3.1.2 Patched				
Time-series of monthly patched rainfall data	mm/10	Gauge No.	PAT	0588573.PAT
3.1.3 Catchment				
Time-series of monthly representative catchment rainfall data	% MAP	Catchment No.	SEC	A42A.SEC
3.1.4 Point				
Time-series of monthly representative point rainfall data	mm	Catchment / dam / site number	RAN	A4R001.RAN
3.2 Streamflow				
3.2.1 Raw				
Time-series of monthly raw gauged streamflow data	million m^3	Gauge No.	MRR	A4H002.MRR
3.2.2 Patched				
Time-series of monthly patched gauged streamflow data	million m^3	Gauge No.	MRP	A4H002.MRP
3.2.1 Raw				

Directory name and location / information description	Units	File name structure		Example
		Name	Exten-sion	
3.2.3 Natural				
Time-series of monthly naturalised extended gauged streamflow data	million m^3	Gauge No.	MRN	A4H002.MRN
3.2.4 natural Incremental				
Time-series of monthly natural incremental streamflow data	million m^3	Catchment No.	INC	A42A1.INC
4. WRSM2000 System Configuration				
WRSM2000 system configuration data files	N/A	Various	Various	122RU.DAT
5. Graphics				
5.1 Maps				
Maps	N/A	Report figure No.	PDF	Figure A-1.PDF
5.2 WRSM2000 system schematic diagrams				
WRSM2000 system schematic diagrams	N/A	Report figure No.	PDF	Figure B-1.PDF

Table 10-2: Information repository for water resource system analyses

Directory name and location / information description	Units	File name structure		Example
		Name	Exten-sion	
1. Documentation				
1.1 Study Documentation				
Study report	N/A	DWAF report No.	PDF	PWMA1/A42/1207.pdf
1.2 Supporting Documentation				
Various documents, as appropriate	N/A	Reference	PDF	DWAF (2005).DOC
2. Hydro-meteorological Data				
2.1 Rainfall				
Time-series of monthly representative catchment / point rainfall data	mm	Catchment No.	RAN	A42A1.RAN
2.2 Streamflow				
Time-series of monthly natural incremental streamflow data	million m^3	Catchment No.	INC	A42A1.INC
3 Stochastic Streamflow Analysis				
3.1 Stochastic Streamflow Testing				
Catchment stochastic streamflow testing data files	Various	Catchment No.	ANS; COR; INC; PIN; PIN2; PIN3; RNK; YER.	Gntstmk5.PIN
Catchment stochastic streamflow testing results	N/A	Catchment No. and test type	CGM	A42A_NMR.CGM
3.2 PARAM.DAT-file				
PARAM.DAT-file	N/A	PARAM*	DAT	PARAM7-1.DAT
4. Desktop IFR Rule Curves				
Quaternary catchment desktop IFR rule curves(2)	million m^3	Catchment No.	TXT	A42A.TXT
5. WRYM System Configuration				
5.1 WRYM Text Data Files				
WRYM text data files for scenario	N/A	*F* and Catchment No.	AFF; DAT; INC; IRR; RAN.	MhlaF01.DAT

Directory name and location / information description	Units	File name structure		Example
		Name	Extension	
5.2 WRYM-IMS Study Export File				
WRYM-IMS Study Export File	N/A	Study name	ZIP	Mhlathuze.ZIP
6. Graphics				
6.1 Maps				
Maps	N/A	Report figure No.	PDF	Figure A-1.PDF
6.2 WRYM system schematic diagrams				
WRYM system schematic diagrams	N/A	Report figure No.	PDF	Figure B-1.PDF
6.3 Long-term YRCs				
Long-term yield-reliability curves	N/A	Figure No.	EMF	Figure G-1.EMF

10.4 Training and technology transfer

The training of and transfer of technology to DWAF staff members that are directly involved with a WAA study is considered to be of key importance. Not only will this serve to develop the competence and expertise of the DWAF staff, but it will also establish a common understanding of technical aspects between the Client and the Study Team and thereby contribute to the overall success of the assignment. Training and technology transfer on a WAA study would typically include two aspects, as shown below. A short discussion on each is provided in the remainder of this section.

- Formal training courses;
- Ad-hoc instruction.

The need may be identified in a particular WAA study for the presentation of a *formal training course*. Such a course was presented as part of the Mhlathuze WAA study and the main points of discussion are provided below for reference purposes. Note that the agenda covered a total of two days and was structured in such a way that sufficient time was available for questions, interaction and group discussions.

- Module 1: Water allocation reform;
- Module 2: Legal aspects in the water allocation process;
- Module 3: Overview of water resource management;
- Module 4: Water resource assessment;
- Module 5: Water resource allocation;
- Module 6: Management of water resource systems;
- Module 7: Intervention planning.

Ad-hoc instruction focussed on technical processes and the application of models and will be aimed at the transfer of technology specifically to DWAF study managers (and will therefore not involve a wider audience). The following distinct instruction methods will be employed:

- *Discussions*: Technical processes are discussed in a workshop environment;
- *Demonstrations*: A specific process or model application is demonstrated by a specialist for the benefit of the trainee;
- *Applications*: The trainee undertakes a process or applies a model practically, under the supervision of a specialist.

A list of topics that may be addressed under ad-hoc instruction is provided below:

- Instruction on water requirements, including:

  - Data sources;
  - Data manipulation and processing;
  - Water user reliability requirements, purpose and application;
  - Format and application of the ecological flow requirements;
  - Water conservation and demand management aspects.
- Instruction on surface hydrological aspects, including:
  - Data collection and sources;
  - Rainfall data preparation and checking;
  - Rainfall data classification, outlier detection and patching;
  - Land-use impacts;
  - WRSM2000 modelling (updated model), including:
    - Model configuration;
    - Model calibration;
    - Generation of natural runoff sequences.
  - Stochastic streamflow hydrology, including:
    - Generation of parameter file (PARAM.DAT);
    - Checking generated streamflow sequences.
- Instruction on groundwater aspects, including:
  - General groundwater module;
  - Lakes module.
- Instruction on water resource analysis, including:
  - Configuration of the WRYM;
  - Model verification;
  - Historical system analysis;
  - Stochastic system analysis;
  - Reconciliation analysis;
  - Result presentation and interpretation.
- General aspects regarding water resource studies, including:
  - Reporting of data and information;
  - Data storage and information management; and
  - Presentation material.

11. MODELLING CONFIDENCE

11.1 Overview

Modelling of water resource systems involves representing a real world system as a computer model using mathematics and decision logic. It is therefore inevitable that the model is a simplification of the real world and that the confidence that can be placed on how well the model represents reality can differ significantly for different situations. Several factors influence the scale of confidence, ranging from the availability of data to the interpretation of the analyst as to what amount to data is sufficient.

A statement of the level of confidence is important and would be used as a means of setting different scales of "safety factors" when the allocation schedule is eventually determined. Typically it could be conceived that the lower the confidence is in the model the lower the portion of the model determined availability would be allocated in practice. As an example, if the confidence in the model is defined as being low one would only allocate, say, 70 % of the model determined available water. In the case of a model being considered to be of high confidence the portion allocated could be as high as, say, 95 % of the model determined available water. The intention with the scale or grading of allowed allocation portions (safety factors) would be to account for the risk of the model being incorrect and allocating water that in reality is not available. The risk that is mitigated through this type of safety factor is to prevent large disruptions in the socio-economic environment when future investigations show the water available is less that what was originally determined.

Quantification of the level of confidence of a model is difficult and no standard method has been developed nor has such a method been implemented. However, it remains important that each WAA study should provide a qualitative statement of the confidence that can be placed on the model produced form the study.

11.2 Review process

A review process has been instituted in all the WAA studies where one of the study teams has been designated to review the work of another team. This process provides a measure of quality control and aims to ensure "best practice" is being followed. Although the main focus of the review would be on the hydrological assessment, which forms the foundation for the assessment, it is recommended that the review include all the steps of the WAA studies. This will ensure that the requirement for consistency between the hydrological database and the eventual water resource model is confirmed.

11.3 Assessment of modelling confidence

As described in a previous section there is no standard means of assessing or quantifying the confidence of a water resource model. It is therefore only possible to provide guidelines as to what could be considered in such an evaluation. Aspects that could be used to define the confidence level that can be placed in a water resources model are presented below:

- Number of rainfall stations per quaternary or per catchment area;
- Length of rainfall records and the success of consistency checks, such as mass plots;
- Accuracy of streamflow measurements used for rainfall-runoff calibration. In some cases low flows are more accurately measured than floods which make it possible to use the data selectively for calibration purposes;
- Reliability of land use information and the estimated impact it has on the water balance;
- Availability of accurate data on the physical characteristics of infrastructure such as reservoirs and transfer conduits;
- Whether modelling elements (such as wetlands and groundwater module) have been verified (directly or indirectly) through actual measurements.

12. RECOMMENDATIONS

It is recommended that this document should be adopted as a guideline for the modelling approach and procedures to be applied in WAA studies. However, in cases where the modelling approach and procedures proposed here are considered to be inadequate or inappropriate, other methodologies may be followed, with comprehensive documentation in this regard providing appropriate motivation.

13. REFERENCES

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Author: Sami, K.

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Author: Sami, K.

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Author: McKenzie, RS.

Note: See **Appendix A**.

Appendix A

Water Availability Assessment Studies for Licensing: Hydrological Review Process (WRP, 2006b)

Appendix B

Lake-Groundwater Interaction Sub-model (Sami, 2006a)

a) Introduction

A *Lake-Groundwater Interaction Sub-model* has been developed and incorporated into the *Groundwater-Surface Water Interaction Model* (see **Section 7**). The *Lake-Groundwater Interaction Sub-model* attempts to encompass the water balance of lakes that interact with regional groundwater, essentially modifying the runoff characteristics of streams discharging from the lake.

The processes simulated include:

- Lake area and level that varies as a function of volume;
- Rainfall and evaporation from the lake area variable;
- Abstraction from fresh water lakes;
- Surface runoff into the lake;
- Surface outflow from the lake as a function of lake level and inflow;
- Groundwater seepage into and out of the lake.

These are shown in **Figure B-1**.

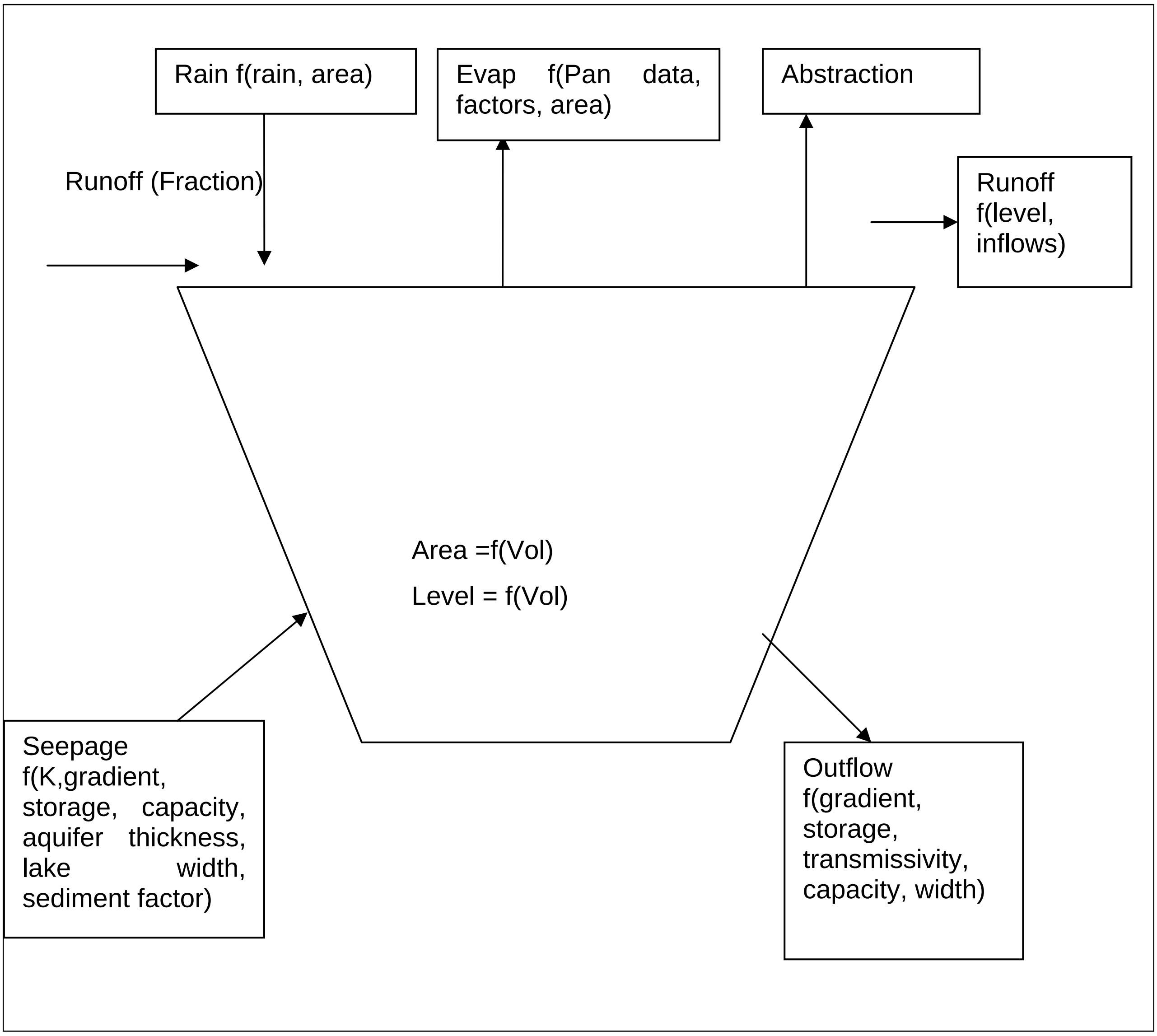


Figure B-1: Structure of the *Lake-Groundwater Interaction Sub-model*

b) Lake water balance

The lake water balance in each month is determined by:

$$\mathbf{VOL_i = VOL_{i-1} + RAIN_i - EVAP_i - ABS_i + RUNIN_i - RUNOUT_i + GWIN_i - GWOUT_i}$$

Where:

VOL	= lake volume
RAIN	= rain
EVAP	= evaporation
ABS	= abstraction
RUNIN, **RUNOUT**	= surface water inflows and outflows
GWIN, **GWOUT**	= groundwater inflows and outflows

c) Lake area-volume and lake level-volume relationships

In order to calculate the water balance components, it is necessary to convert monthly lake volumes to an area. This is accomplished by:

$$AREA = a * LN(VOL) + b$$

and

$$LEVEL = a * LN(VOL) + b$$

Where:

a, **b** = regression parameters determined from a lake bathymetric survey

Note: The parameters **a** and **b** can vary for the area and level relationships.

d) Rainfall

Rainfall increments onto the lake are calculated by:

$$RAIN = RAIN_i * AREA * LAKEMAP/MAP$$

Where:

$RAIN_i$ = monthly rainfall from WR90 or WRSM2000

LAKEMAP = annual MAP measured at the lake

MAP = annual MAP for the quaternary catchment

This equation allows rainfall to vary between the lake and the quaternary catchment to account for inter catchment variability, and allows rainfall increments to vary with fluctuating lake area.

e) Lake evaporation

Lake evaporation is calculated by:

$$EVAP = EVAP_i * AREA * PAN * EVAPFACT$$

Where:

$EVAP_i$ = monthly pan evaporation determined from MAE * the average monthly annual fraction of evaporation. This data is obtained from WR90/2000.

PAN = the appropriate monthly pan factor to convert pan data to open water evaporation

To account for inter annual variability in monthly evaporation in wet and dry years a correction factor **EVAPFACT** is applied:

$$\mathbf{EVAPTFAC_i = RAINavg * MAP / RAIN_i}$$

Where:

RAINavg = average monthly rainfall as a fraction of MAP

RAIN = monthly rainfall from WR90

EVAPFACT is a factor to account for whether that month is drier or wetter than average, numbers greater than 1 being wetter than average and less than 1 being drier than average.

If EVAPFACT < 1 then EVAPFACT= 0.5*EVAPFACT + 0.5

If EVAPFACT>1 then EVAPFACT = $\text{EVAPFACT}^{0.17}$

EVAPFACT was determined from regression relationships of monthly evaporation and rainfall at lake Mzingazi. The effect is make monthly evaporation lower than the monthly average evaporation in wetter than average months, and higher than average in drier than average months.

f) Abstraction

Abstraction from freshwater lakes is entered as a monthly volume and directly removed from the lake monthly water volume variable (VOL).

g) Surface water inflow

Surface water inflow is calculated from the Pitman model Quaternary catchment runoff times a parameter of the fraction of the catchment area that contributes runoff to the lake

h) Groundwater seepage into the lake

Due to the dynamics of lake area versus aquifer thickness, inflow from aquifers into lakes generally varies around the lake perimeter, generally being much greater near the shoreline and diminishing exponentially towards the centre of the lake.

For this reason, groundwater inflows are calculated in bands around the lake representing 1, 2, 4, 6, 8, 10, 20 and 100 % of the distance towards the centre of the lake. In each band, inflow is calculated by:

GWIN = HGRAD * (STORE – SWL)/(TAS – SWL) * 30 * K * CONDUCTANCE

Where:

HGRAD, **STORE**, **SWL** and **TAS** are parameters from the surface-groundwater interaction module and are defined in **Appendix C** of this report.

K = permeability of the aquifer

CONDUCTANCE = is a correction factor for each band relating band area to lake width and length to permeability.

i) Groundwater seepage out of the lake

Groundwater seepage out of the lake is calculated by:

GWOUT= HGRAD * (STORE – LAKESWL)/(TAS – LAKESWL) * 30 * WIDTH * T

Where:

LAKESWL = is the lake level at which groundwater outflow ceases, (usual 0, or the bottom of the lake)

T = aquifer transmissivity

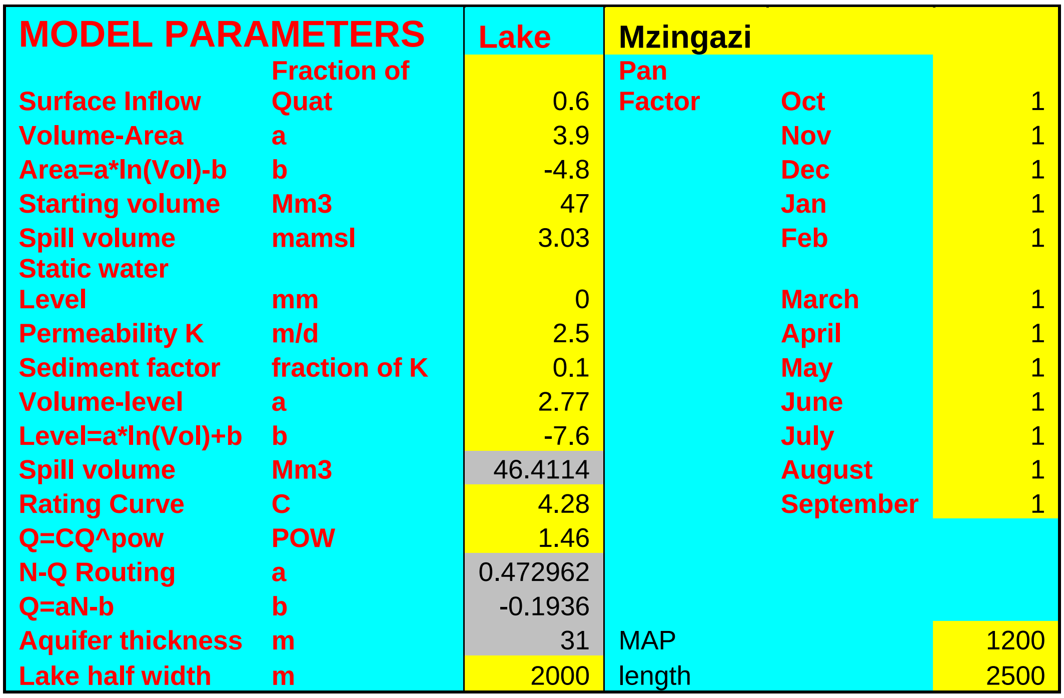
j) Surface water outflow

Surface water outflow is calculated using level pool routing, if lake level exceeds a minimum lake spill level parameter. The water balance for **Section (d)** and **(j)** is calculated as a two month moving average and the routing parameters are calculated from weir rating curve parameters.

k) Parameters

The parameters required for the lake module area are shown below, with parameters highlighted in grey being derivative parameters calculated elsewhere.

Table B-1: Parameters of the Lake-Groundwater Interaction Sub-model



MODEL PARAMETERS		Lake	Mzingazi		
Surface Inflow	Fraction of Quat	0.6	Pan Factor	Oct	1
Volume-Area	a	3.9		Nov	1
Area=a*ln(Vol)-b	b	-4.8		Dec	1
Starting volume	Mm3	47		Jan	1
Spill volume	mamsl	3.03		Feb	1
Static water Level	mm	0		March	1
Permeability K	m/d	2.5		April	1
Sediment factor	fraction of K	0.1		May	1
Volume-level	a	2.77		June	1
Level=a*ln(Vol)+b	b	-7.6		July	1
Spill volume	Mm3	46.4114		August	1
Rating Curve	C	4.28		September	1
Q=CQ^pow	POW	1.46			
N-Q Routing	a	0.472962			
Q=aN-b	b	-0.1936			
Aquifer thickness	m	31	MAP		1200
Lake half width	m	2000	length		2500

l) Outputs

The module generates monthly time series of lake levels and lake outflows, which can be calibrated against observed data.

Figure B-2 shows model simulations against observed discharge from Lake Msingazi. The gauging weir is unable to measure high flows, so peak flows cannot be calibrated. **Figure B-3** shows simulated lake levels. Electronic data on lake levels could not be obtained and the lake level was calibrated visually against recorded lake levels taken at periodic intervals.

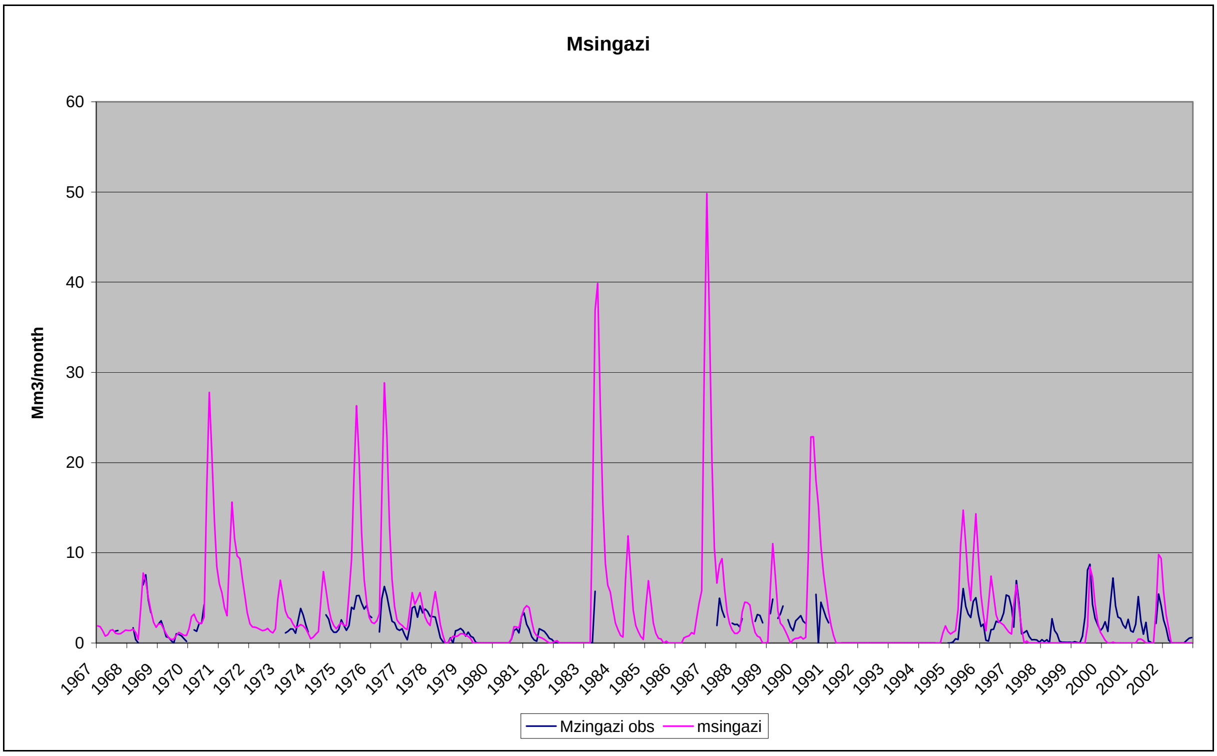


Figure B-2 Simulated and observed discharge from Lake Msingazi

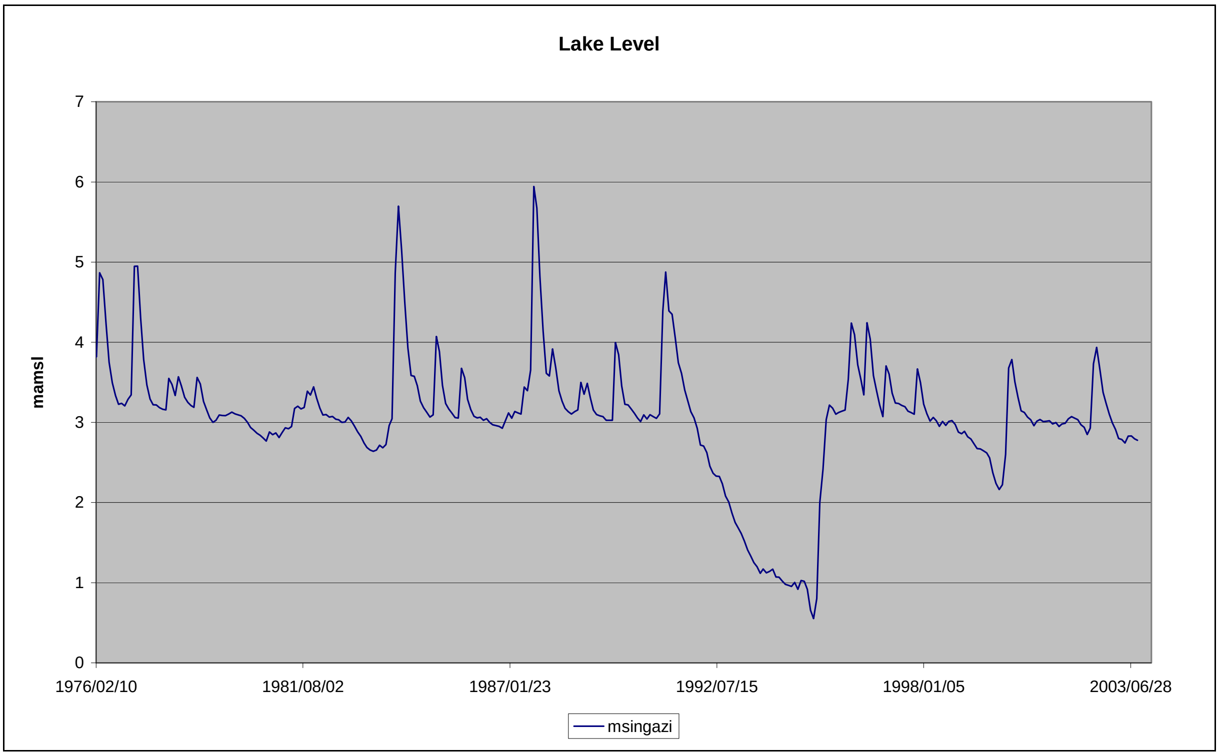


Figure B-3 Simulated lake levels for Lake Msingazi

Appendix C

Groundwater-Surface Water Interaction Model (Sami, 2006b)

a) Introduction

Background

The following section describes the proposed module for surface-groundwater interaction.

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

The methodology was developed as part of the DWAF *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 module was developed as part of *Project 3B, Groundwater-Surface Water Interactions*. 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;
- A database populated.

A methodology and algorithms were developed whereby the impacts on base flow 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 base flow occurs.

Subsequently, the software found application in simulating the potential impacts of groundwater abstraction on the time series of base flow 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 part of the Pitman model in WR2005 in order to simulate baseflow nationwide.

Further modifications were made after a review process as part of Activity 7 of the DWAF *Geo-hydrological Software Development* project.

In addition to preliminary nationwide estimates of groundwater base flow 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);
- Klein Dwars: To determine impacts on inflows to De Hoop dam from a proposed wellfield for Amplats in the Klein Dwars alluvium (AMPLATS).

Assumptions and limitations of the proposed module

The proposed module depends on several assumptions and encounters a number of limitations listed below:

- Base flow depletion due to groundwater abstraction as well as groundwater outflow from the catchment (**Section (b)**) is calculated using a Darcian approach, i.e. assuming an equivalent porous media. It has to be corroborated whether this approach is valid for a fractured/secondary or karstified aquifer system. Depending on the degree of fracturing and fracture interconnectivity a secondary or karstic aquifer can be represented as an equivalent porous media on a Quaternary catchment scale. The module was successfully to the Schoonspruit dolomitic compartment and could represent baseflow depletion due to groundwater abstraction.
- The base flow depletion calculation (**Section (b)**) assumes that all abstraction takes place from the regional aquifer, not from perched aquifers.

- The base flow depletion calculation (**Section (b)**) uses the weighted mean distance of abstraction points from the main channel to address the cumulative effects of groundwater abstraction in the catchment can be addressed.
- The hydro-geological parameters of the model are determined with water balance approaches and averaged over a Quaternary catchment scale. Though they might resemble hydro-geological parameter determined on a local scale during hydrogeological field investigations, they usually differ from these physically based local parameters and should not be used as such.

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 basef low to river channels, either to perennial effluent or intermittent streams;
  - Seepage to permanent or temporary wetlands;
  - Seepage from or to reservoirs and lakes;
  - 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 groundwater table lies at some depth below the channel;
  - Induced recharge caused by pumping of aquifer systems in the vicinity of rivers causing a flow reversal.

Streams in natural channels in arid and semiarid regions are usually ephemeral. Flow is occasional and follows storms, which are infrequent. When flood flows occur in normally dry stream channels, the volume of flow is reduced by infiltration into the bed, the banks, and possibly the flood plain. These losses to infiltration are called transmission losses.

- Those involving both losses and gains to streamflow depending on stage:
  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 base flow as part of stream runoff, hence an allocable surface resource. Geo-hydrologists often consider groundwater resources in terms of recharge, a large portion of which generates base flow. Consequently, the simple addition of surface water runoff volumes and groundwater resources based on recharge (i.e. Harvest Potential) double accounts for the base flow component.

The quantification of these processes is severely hampered by miscomprehension of the terminologies used by hydrologists, ecologists and geo-hydrologists. Streamflow originating from subsurface pathways and contributing to base flow is often all termed groundwater by hydrologists and ecologists, as well as some geo-hydrologists, 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 base flow originating from the regional aquifer and base flow originating from other subsurface pathways.

Base flow, 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:

- The regional groundwater body (**groundwater base flow**), that portion of the total water resource that can either be abstracted as ground water or surface water, or
- 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 base flow 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. Base low to maintain in-stream 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 base flow. 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 base flow in the river.

Similarly, groundwater base flow cannot be simply equated to recharge, since a portion of recharge may be lost before reaching the regional aquifer through seepage of percolating water in outcropping fractures, springs draining perched water tables, artesian springs, evapo-transpiration, or losses to deep lying regional groundwater which discharges at a great distance from the point of recharge. For these reasons, groundwater base flow 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 base flow is significant.

Base flow is often subdivided into: interflow not originating from the regional groundwater body and therefore not accessible by boreholes; and groundwater base flow. 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 spring flow.

Many publications have noted that base flow 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 used in numerical flow models, 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 base flow occur for small head changes when the head difference is small, but base flow approaches some maximum value as the head difference becomes larger.

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 base flow. 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.

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 (base flow depletion, reduced groundwater outflow from the catchment, or reduced evapo-transpiration losses from groundwater due to a lowering of water levels). Once new equilibrium conditions are reached whereby pumping is balanced by base flow 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 base flow 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 base flows. In general, a tenfold increase in distance from a surface water course will result in a hundred fold increase in response time. Recharge is unimportant in terms of the magnitude of the impact on base flow; however, it limits the pumping rate since the portion originating from the aquifer cannot exceed recharge.

b) Proposed methodology

Structure of methodology

The logical stepped methodology utilises a time series of the Pitman S variable (subsurface storage) from WRSM2000 as input data, from which a time series of recharge is generated. This approach provides a direct link to the Pitman model. Interflow and groundwater base flow are derived independently and used to simulate base flow to the catchment hydrograph.

The methodology is based on:

- Utilising the catchment soil moisture time series (Pitman S) generated by the WRSM2000 to calculate a time series of recharge;
- Incrementing a percolating storage by recharge, with any recharge in excess of percolating storage capacity being dumped to aquifer storage;
- Calculating interflow from the percolating storage utilising the Pitman methodology;
- Incrementing groundwater storage from the percolating storage up to a maximum recharge rate, with any recharge in excess of the maximum recharge rate contributing to interflow;
- Depleting groundwater storage by evapo-transpiration and groundwater outflow to other catchments as a function of groundwater storage until static water level conditions are reached;
- Calculating groundwater base flow or transmission losses in a non-linear manner as a function of groundwater storage and runoff volume;
- Depleting groundwater storage and groundwater base flow 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 C-1**.

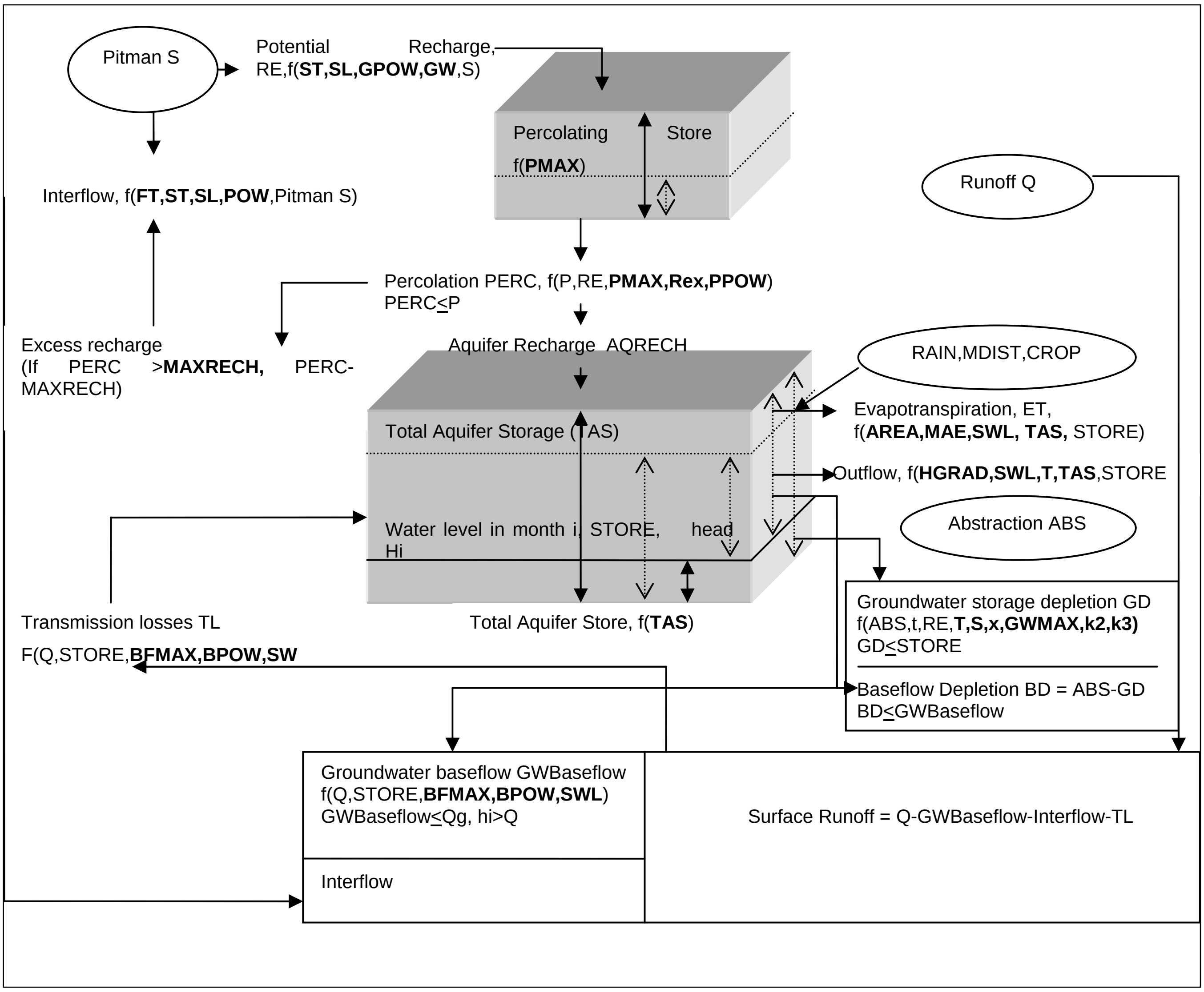


Figure C-1: Structure of the new interaction methodology (parameters are indicated in bold)

Interflow from the percolating store

From the time series of Pitman S input to the model interflow is generated using the Pitman algorithm, with Qg being the interflow component:

$$Qg = FT\left(\frac{S - SL}{ST - SL}\right)^{POW} \qquad \textbf{(Eq. C-1)}$$

Where:

S = variable of Pitman S (subsurface moisture storage in mm) for each month

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

Parameters for **SL**, **ST**, **FT** and **POW** are obtained from WRSM2000. If all base flow is to be generated exclusively as interflow, then parameter values for **SL**, **ST**, **FT** and **POW** from WRSM2000 are utilised. Since the Pitman model generates base flow solely from the above equation, if groundwater base flow is to be generated parameters for SL and FT must be increased and reduced respectively from WRSM2000 default values in order to reduce the interflow component (**Figure C-2**). In general **SL** is increased to the point where no interflow is generated during dry periods (**SL** set to somewhat higher than **S** values during dry periods).

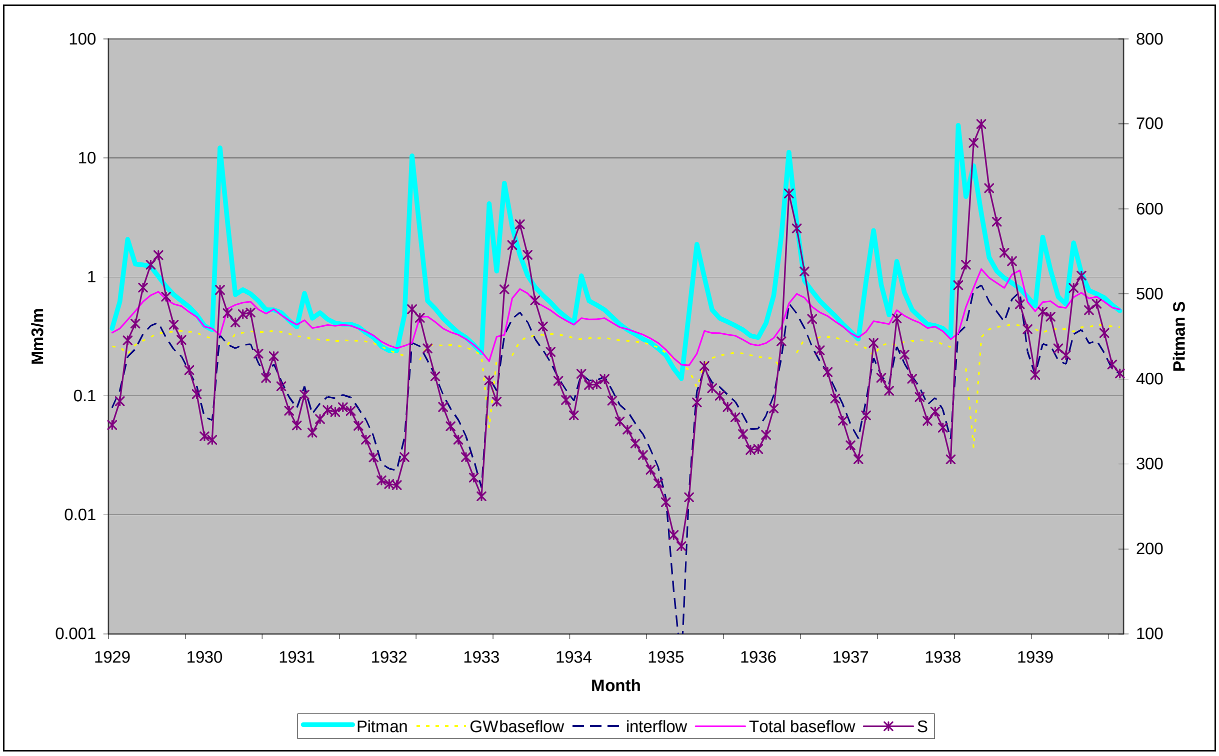


Figure C-2: Hydrograph and Pitman S generated using Pitman model for B82B using SL=0, ST=800, FT=4.7 and POW=2, and Interflow generated using SL=190, ST=800, FT=3 and POW=2

Estimation of recharge

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

$$RE = GW\left(\frac{S - SL}{ST - SL}\right)^{GPOW} \qquad \textbf{(Eq. C-2)}$$

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 and 3. Parameter values are regional in nature and have been found to need little or no calibration between quaternaries with similar conditions.

GPOW is generally kept equal to Pitman **POW** and **GW** is calibrated until mean annual recharge estimates approximate published values. **GPOW** generally lies from 0 to 20 % higher than **POW**.

The output of the algorithm is a monthly time-series of recharge. Since recharge and the Pitman S input data are not lagged relative to rainfall, recharge is directly related to monthly rainfall. The lag between rainfall and base flow generation may be significant in some aquifers (**Figure C-3**).

If recharge were input directly to the regional aquifer, large unrealistic variations in groundwater base flow could arise. Recharge therefore needs to be 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.

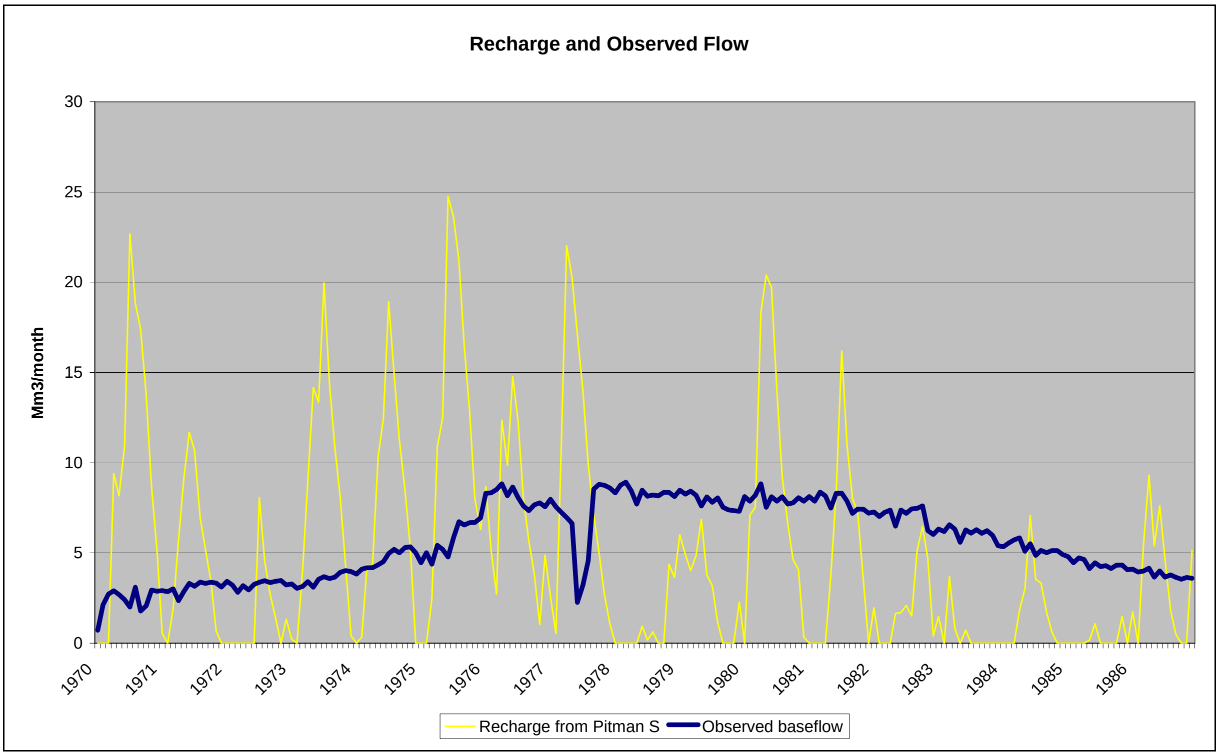


Figure C-3: Recharge hydrograph relative to groundwater discharge from the Schoonspruit eye. GW=35, GPOW=1, ST=600, SL=220 and recharge = 39 mm/a

Percolating storage increments from recharge

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:

$$PERC = RE_x \times \left(\frac{P}{PMAX}\right)^{PPOW} \times \frac{RE_x}{\overline{RE}} \qquad \textbf{(Eq. C-3)}$$

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

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 C-4**).

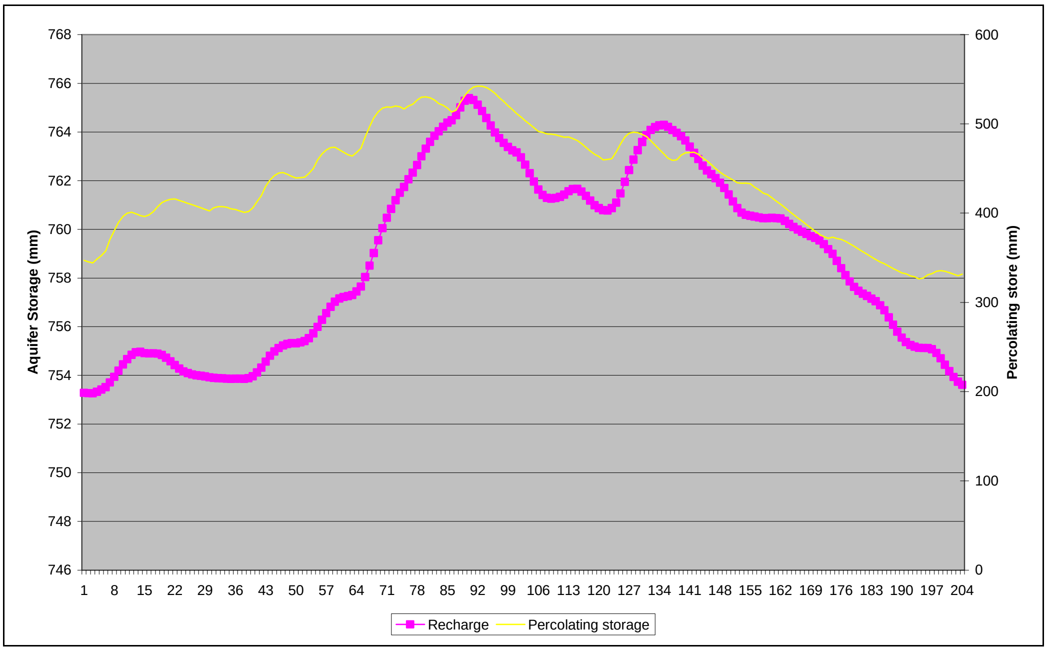


Figure C-4: Aquifer storage and percolating storage

The addition of the percolating store is to lag recharge **RE** generated from the soil using a moving average of recharge (**REx**) and the level of storage relative to the maximum volume of the percolating zone. Using this approach, percolation **PERC** is similar to the moving average of recharge (**Figure C-5**).

Default values for **PMAX** and **REx** for every quaternary catchment have been incorporated into WRSM2000.

Percolation **PERC** from the percolating storage is incremented directly to aquifer storage **STORE**, if the maximum recharge rate is not exceeded (**MAXRECH**). If the maximum recharge rate is exceeded, excess recharge 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. C-2**. A time series of aquifer storage is thereby generated (**Figure C-5**).

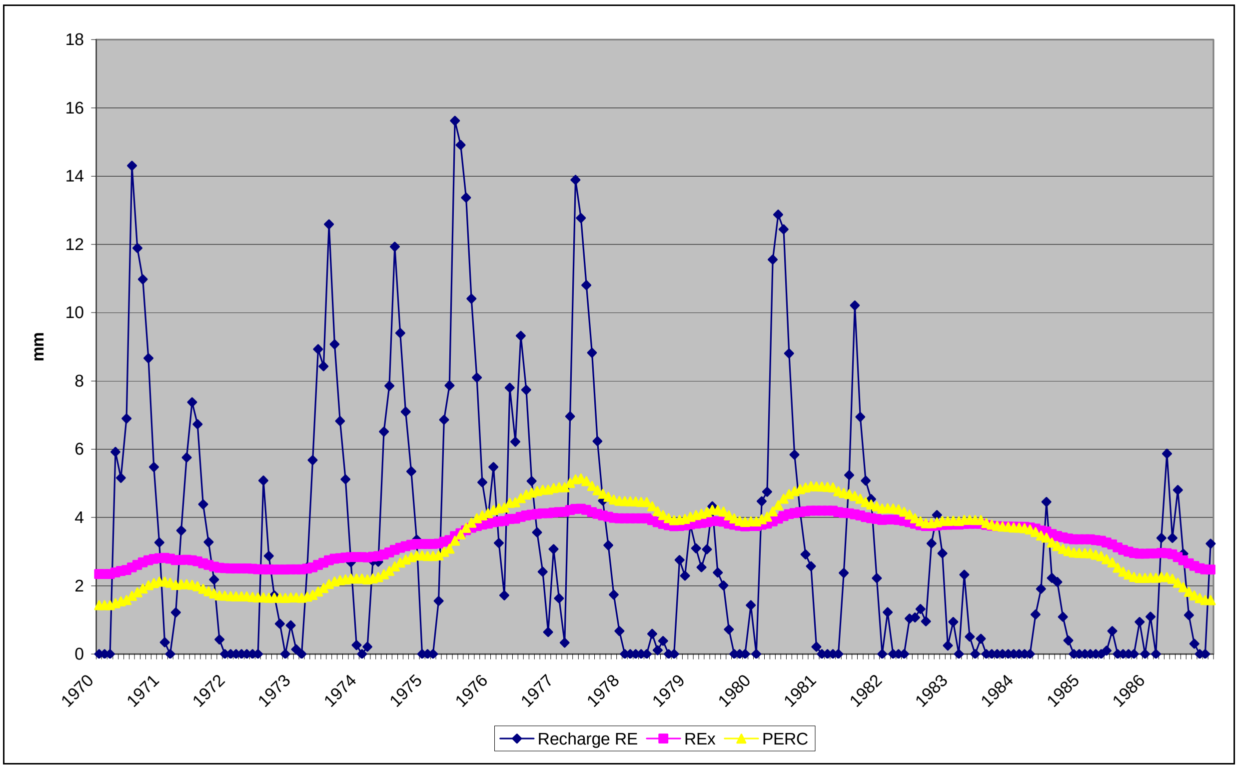


Figure C-5: Recharge RE the 132 month moving average of recharge Rex and the percolation to the aquifer PERC

Evapo-transpiration from shallow groundwater

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 or WRSM2000. 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 evapo-transpiration can take place. Monthly evapo-transpiration is calculated by the product of mean annual evaporation, monthly distribution and crop factor. Rainfall is subtracted from evapo-transpiration to obtain evapo-transpiration demand from groundwater. When rainfall exceeds evapo-transpiration demand evapo-transpiration from groundwater is defaulted to 0, since it is assumed that the evapo-transpiration demand will be met from soil moisture storage.

Evapo-transpiration demand is multiplied by an aquifer storage factor to allow evaporation to decrease as groundwater storage is depleted. Evapo-transpiration occurs at the maximum rate when groundwater storage is at or above total aquifer storage (**TAS**) and declines towards 0 as groundwater storage drops to a level below the stream channel, defined by a parameter of static water level.

Evapo-transpiration from groundwater is therefore calculated by:

$$((MAE \times MDISTxCROP) - RAIN) \times AREA \times (STORE - SWL/(TAS - SWL) \qquad \textbf{(Eq. C-4)}$$

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
TAS =Total aquifer storage from GRA II total aquifer volume divided by area

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

Evapo-transpiration is subsequently decremented from groundwater storage.

TAS can be obtained from either the Map of *National Groundwater Resources Map of South Africa* as the product of 'Recommended Drilling Depth Below Groundwater Level' and storativity. Or from the GRA II database of total aquifer volume.

SWL is calculated as **TAS** less the degree of annual groundwater level fluctuation (in mm) times storativity. Hence the static water level can be expected to be 20 to 50 mm less than **TAS**, depending on the nature of the aquifer.

Default static water levels (**SWL** and Total aquifer storage (**TAS**) have also been included for every quaternary catchment in WR2000.

Groundwater Outflow

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:

$$HG = HGRADx(STORE - SWL)/(TAS - SWL) \qquad \textbf{(Eq. C-5)}$$

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.

Groundwater base flow and transmission losses

After evapo-transpiration and groundwater outflow have been decremented from groundwater storage, groundwater base-flow is calculated. Groundwater base-flow 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 base-flow 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:

$$GWBaseflow = (1 - e^{(HEAD \times BPOW)}) \times BFMAX \qquad \textbf{(Eq. C-6)}$$

Where:

BFMAX= parameter of the maximum rate of groundwater baseflow

BPOW = relationship between head difference and baseflow

$$HEAD = STORE - SWL - \frac{RUNOFF}{CATCHMENT} \qquad \textbf{(Eq. C-7)}$$

Where:

RUNOFF = Input of streamflow

CATCHMENT = Catchment area

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

This equation allows large increases in base flow or transmission losses for small head changes when the head difference between surface and groundwater is small, but causes base flow and transmission losses to approach the maximum value of BFMAX as the head difference becomes larger (**Figure C-6**). As the head difference increases, the exchange of water thereby increases at an increasingly smaller rate.

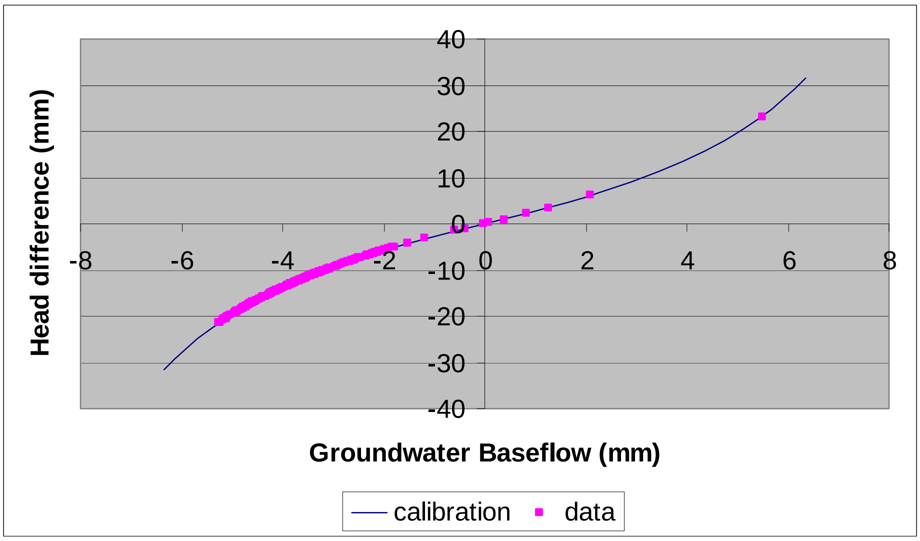


Figure C-6: Relationship between groundwater baseflow (-ve) and difference in head (HEAD) between groundwater storage and surface water. +ve base flow values imply influent conditions when transmission losses occur. Maximum base flow has been set at 8 mm/month. TAS-SWL = 40 mm

Interflow

Interflow is calculated as the sum of interflow from the percolating store (3, 2) and percolation **PERC** in excess of the maximum recharge rate **MAXRECH**:

$$INTERFLOW = FT\left(\frac{S-SL}{ST-SL}\right)^{POW} + (PERC - MAXRECH)\text{, if PERC>MAXRECH} \qquad \textbf{(Eq. C-8)}$$

Interflow is lagged using the Pitman lag algorithm:

$$QLAG = QLAG_{t-1} + \left[\left(INTERFLOW_{t-1} - QLAG_{t-1}\right) * \left(\frac{1}{GL+0.5}\right)\right] + \left[\left(\frac{1}{GL+0.5} * 0.5\right) + \left(INTERFLOW - QLAG_{t-1}\right)\right]$$

(Eq. C-9)

Where:

QLAG = Lagged interflow

GL = Pitman lag parameter

t-1 = denotes flows from the previous month

Groundwater Abstraction

It is assumed that all abstraction takes place from the regional aquifer, not from perched aquifers.

Groundwater abstraction can deplete both groundwater storage and groundwater base flow 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:

$$t' = \frac{4Tt}{x^2 S} \qquad \%GW = \frac{GWMAX}{(1 + e^{(k3 + k2 \times t')})}$$ **(Eq. C-10)**

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 base flow 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 C-7** for a borehole at various distances from the river. Over time, progressively more base flow depletion occurs, however, this transition is distance dependent.

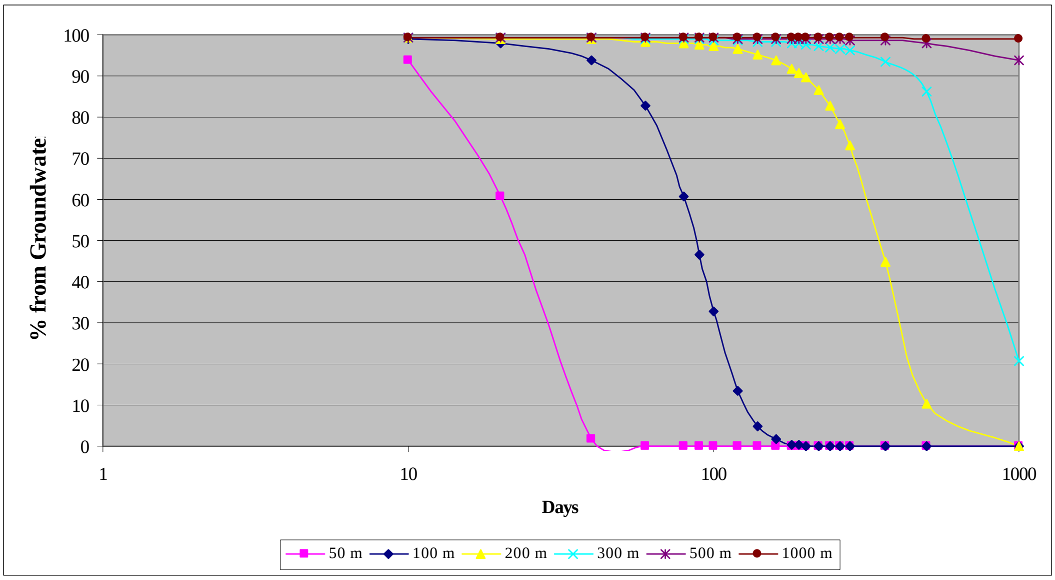


Figure C-7: Impact of groundwater abstraction on base flow depletion at various distances from the channel

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. C-12** is modified by recharge, thereby allowing recharge to modify the impact on storage. This is achieved by:

$$if\ \frac{\mathrm{Re}ch\arg e_i orPERC_i}{Meanmonthlyrech\arg e} < 1, then, t = (1 - \frac{\mathrm{Re}ch\arg e_i orPERC_i}{meanmonthlyrech\arg e})x30 + t_{i-1}$$ **(Eq. C-11)**

$$if\ \frac{\mathrm{Re}ch\arg e_i}{Meanmonthlyrech\arg e} > 1, then, t = t_{i-1} - (\frac{\mathrm{Re}ch\arg e_i}{meanmonthlyrech\arg e} - 1)x30$$ **(Eq. C-12)**

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 base flow depletion to slow down during drier periods depending on the recharge volume.

The depletion of groundwater base flow (**Depletion**) is calculated by:

$$Depletion = \frac{100 - \%GW}{100} xAbstractionx \frac{\mathrm{Re}ch\arg e_i orPERC_i}{Meanmonthlyrech\arg e}$$ **(Eq. C-12)**

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 base flow does not become evident following recharge events after prolonged abstraction due for the need to re-water the aquifer to some extent before base flow can occur.

The balance of abstraction volumes (abstraction-depletion) is taken from **STORE**. Depletion is subtracted from calculated groundwater base flow (**GWBaseflow**), thereby depleting base flow. If calculated base flow 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**.

c) Data input

The parameters required and comments on the source of data are shown in **Table C-1**.

NOTE:

It must be clearly stated, that the hydro-geological parameters of the model represent averaged Quaternary scale catchment parameters determined with water balance approaches (e.g. total aquifer volume from GRA II) or fit parameter of the current water balance model (e.g. maximum recharge rate).

Though they might resemble hydro-geological parameter determined on a local scale during hydro-geological field investigations, they usually differ from these physically based local parameters and should not be used as such.

Table C-1: Components of the *Groundwater-Surface Water Interaction Model*

[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	WR90/2000.	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, WR2000	Determines total aquifer storage (TAS). 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, WR2000	Determines total aquifer storage (TAS). 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
Total Aquifer Storage	C	Calculated internally from Storativity and aquifer		Affects aquifer storage level at	Depends on aquifer thickness and	

(TAS)		thickness, or from GRA II		groundwater evapotranspiration and outflow reache their maximum rate	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 total aquifer storage. 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	WR90/2000	Controls evapotranspiration	Used to calculate monthly rainfall from WR90 monthly rainfall distribution files		None
Static water level (SWL)	P	WR2000, Calibrated regionally. Generally set to TAS – 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 TAS. It is generally more than 50% of TAS in shallow or weathered aquifers and higher in deep seated fractured aquifers with little baseflow	30-80% of TAS	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, WR2000	Controls rate at which recharge percolates to	Used to lag the time between recharge and the groundwater	10-400	Increasing causes recharge to be more attenuated and

			aquifer	baseflow response		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
MAXRECH	P	Calibration	Maximum recharge rate	Controls rate of recharge to account for low vertical permeability layers. Reducing the value generates less aquifer recharge and groundwater baseflow and more interflow		
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, WR2000	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
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 recharge parameters must be calibrated.
PITMAN PARAMETERS						
FT	P	WR90/2000	Controls rate of interflow from the soil zone	Generally obtained from regional WR90 data. In catchments with no baseflow WR90 sets this parameter to 0. It is used to generate only the portion of total baseflow from interflow hence must be less than the value used in the Pitman model	WR90 value or less	Calibrated to less than WR90 value if groundwater baseflow is to be generated. Increasing value cause interflow to increase and be more responsive
ST	P	WR90/2000	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	WR90/2000	Determines soil moisture level at which interflow and recharge stop, hence controls recharge and	Generally obtained from regional WR90 data. Used as a threshold for recharge and interflow from the soil zone and set to	WR90 value or higher	Decreasing value causes interflow and recharge to be more persistent and increases volumes

			interflow volumes	allow interflow to stop or have very low value during dry periods		
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.	WR90 value	Not calibrated
GW	P	WR90/2000, Calibrated	Controls potential recharge	This parameter is generally set slightly higher than FT in WR90 and calibrated to achieve a groundwater balance between recharge and outflow	>FT	Increasing increases potential recharge. Calibrated so that mean annual recharge approximates published values.
GPOW	P	WR90/2000	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.
GL	P	WR90/2000	Lags Interflow	Generally set from WR90 data	0-2.5	If Interflow appears to peaky, this parameter can be increased to attenuate peaks and increase low flows
Harvest	D	WSAM	Not used in model	Included only as an		

Potential				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	Controls groundwater baseflow volumes and maximum baseflow It is set to a low value (1 or 2 mm) in low permeability aquifers and to a high value (3-5 mm) in permeable aquifers:	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	WR90/2000	Affects	Generally obtained		

			groundwater evaporation	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

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	Used for calibration purposes and to derive surface water head used to calculate groundwater baseflow			
Pitman S (S)	D	Pitman model	Driving input of model			

Rainfall (RAIN)	D	WR90/2000	Affects evapotranspiration	Used only to determine rate of groundwater evapotranspiration		
% of MAE (MDIST)	D	WR90/2000	Affects temporal distribution of evapotranspiration	% monthly distribution of MAE. Used to distribute MAE between months		
Crop factor (CROP)	D	WR90/2000	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		