



water affairs

Department:
Water Affairs
REPUBLIC OF SOUTH AFRICA

ESTABLISHMENT OF A REAL TIME OPERATING DECISION SUPPORT SYSTEM FOR THE SABIE- SAND RIVER SYSTEM

MAIN REPORT



APRIL 2013

APPROVAL

Report Title	Main Report
Study Name	Establishment of a Real Time Operating Decision Support System for the Sabie-Sand River System
<hr/>	
Report number	
Submitted by	IWR Water Resources (Pty) Ltd
Authors	T Sawunyama, S Mallory and P Odendaal
Report Status	: Final
Date	: April 2013

Professional Service Provider: IWR Water Resources (Pty) Ltd.

Approved on behalf of the Professional Service Provider by:

.....

S Mallory
Director

DEPARTMENT OF WATER AFFAIRS

Directorate: Water Resource Planning Systems

Approved for Department of Water Affairs:

.....

Dr B. Mwaka
Project Director

.....

Mrs C Ntuli
Project Manager

TABLE OF CONTENTS

TABLE OF CONTENTS	ii
LIST OF FIGURES	iii
LIST OF TABLES.....	iv
LIST OF ABBREVIATIONS.....	vi
1 INTRODUCTION	1-1
2 SCOPE OF WORK	2-1
3 DESCRIPTION OF STUDY AREA.....	3-1
3.1 CLIMATE.....	3-1
3.2 TOPOGRAPHY	3-1
3.3 GEOLOGY AND SOILS.....	3-1
3.4 VEGETATION.....	3-2
4 HYDROLOGY.....	4-1
4.1 NATURAL HYDROLOGY	4-1
4.2 REAL TIME HYDROLOGY	4-1
4.2.1 Introduction.....	4-1
4.2.2 Theory of rainfall-runoff process	4-1
4.2.3 Model calibration.....	4-7
4.3 SABIE-SAND DAILY MODELLING APPROACH	4-7
5 WATER REQUIREMENTS	5-1
5.1 DOMESTIC WATER USE.....	5-2
5.1.1 Actual water use	5-2
5.2 IRRIGATION WATER USE.....	5-5
6 WATER INFRASTRUCTURE	6-1
6.1 DAMS AND ABSTRACTION POINTS	6-1
6.1.1 Dams.....	6-1
6.1.2 Abstraction points	6-4
6.2 WATER DISTRIBUTION INFRASTRUCTURE	6-7
6.2.1 Bulk Water Supply scheme.....	6-7
6.2.2 Water Transfers.....	6-10
6.2.3 IRRIGATION SCHEMES AND CANALS.....	6-10
7 ECOLOGICAL RESERVE.....	7-1
8 INTEGRATION OF DECISION SUPPORT MODELS	8-1
8.1 ANNUAL WATER ALLOCATION AND CURTAILMENT MODEL.....	8-3
8.1.1 Setting up water resources model.....	8-3
8.1.2 Medium term operation (Water use rationing model)	8-4
8.1.3 Long-term operation (Water Allocation model).....	8-5
8.2 RAINFALL-RUNOFF MODEL	8-5
8.3 REAL TIME RESERVE MODEL	8-9
8.4 RIVER FLOW MANAGEMENT (WATER ADMINISTRATION SYSTEM (WAS))	8-12
9 MONITORING FOR REAL TIME MANAGEMENT	9-1
9.1 REAL TIME RAINFALL STATIONS	9-5
9.2 REAL TIME FLOW GAUGES	9-5
9.2.1 Champagne Site.....	9-6
9.2.2 New Forest Site	9-6
9.2.3 Dingleydale Site.....	9-8
9.2.4 Hydraulic data collection	9-8

9.2.5	Hydraulic data modelling.....	9-9
9.2.6	Flow gauge installation	9-10
9.2.7	Cross-sectional profiles.....	9-12
10	INFORMATION SHARING AND MANAGEMENT STRUCTURE.....	10-1
10.1	INFORMATION SHARING	10-1
10.2	MANAGEMENT STRUCTURE.....	10-3
11	CONCLUSIONS AND RECOMMENDATIONS.....	11-1
11.1	CONCLUSIONS.....	11-1
11.2	RECOMMENDATIONS	11-2
12	REFERENCES.....	12-1

LIST OF FIGURES

Figure 1.1	Overview map of Sabie-Sand River System	1-2
Figure 2.1	River flow management using Water Administration System	2-2
Figure 2.2	Passive river flow management.....	2-2
Figure 4.1	Rainfall-runoff processes	4-2
Figure 4.2	Incremental runoff response due to a rainfall event.....	4-3
Figure 4.3	Samples of rapid decline in runoff following a runoff event.....	4-4
Figure 4.4	Combining surface runoff and baseflow	4-6
Figure 5.1	Allocation versus actual abstractions at Inyaka WTWs	5-4
Figure 6.1	Da Gama Dam (X3R001) Area-Capacity relationship (DWAf 2009).....	6-3
Figure 6.2	Inyaka Dam (X3R002) Area-Capacity relationship (DWAf 2009)	6-3
Figure 6.3	Domestic and irrigation pump abstraction points in Sabie-Sand River System.....	6-4
Figure 6.4	Layout of diversion works in the Sand River catchment (DWAf, 2003).....	6-5
Figure 6.5	Schematic layout of the Bushbuckridge to Acornhoek bulk water supply scheme (DWAf 2009b)	6-8
Figure 6.6	Schematic layout of Dwarsloop/Thulamahashe bulk water supply scheme (DWAf 2009b)	6-9
Figure 6.7	Schematic layout of the Marite bulk water supply scheme (DWAf 2009b).....	6-9
Figure 8.1	Framework for DSS for the Sabie-Sand River System.....	8-2
Figure 8.2	Restriction rules at different storage levels.....	8-4
Figure 8.3	Monthly reservoir probability trajectories.....	8-5
Figure 8.4	Calibration parameters of daily rainfall-runoff model	8-6
Figure 8.5	Illustration of validation of forecast rainfall with rain gauge data at Emmet Gauging Station	8-7
Figure 8.6	Forecast rainfall input file	8-8
Figure 8.7	Forecast flows output screen	8-8
Figure 8.8	Comparison of monthly forecasted flows with historical flows	8-9
Figure 8.9	Reserve model input file.....	8-10
Figure 8.10	Illustration of observed flows at Kruger Gate	8-11
Figure 8.11	Weekly Reserve output graph	8-12
Figure 8.12	Importing flow and water use data into WAS	8-14
Figure 8.13	Define the week	8-14
Figure 8.14	Running the release module.....	8-15
Figure 8.15	Comparison of calculated releases and measured releases.....	8-15
Figure 9.1	Real time rainfall and flow gauges	9-2

Figure 9.2	Real time implementation of operating rule at Dingleydale weir	9-3
Figure 9.3	Champagne cross-section (red line) selected for rating of streamflow gauge.....	9-6
Figure 9.4	Flow measurements at New forest irrigation canal.....	9-7
Figure 9.5	New Forest cross-section (black line) selected for rating streamflow gauge.....	9-7
Figure 9.6	Dingleydale cross-section selected for rating streamflow gauge	9-8
Figure 9.7	Installation of River Flow Gauges	9-11
Figure 9.8	Installation of canal flow gauges.....	9-11
Figure 9.9	Cross-sectional profile for Champagne site showing water and gauge plate level.....	9-12
Figure 9.10	Measured and modelled rating data and functions for Champagne site	9-12
Figure 9.11	Cross-sectional profile for New Forest river site showing water and gauge levels	9-13
Figure 9.12	Measured and modelled rating data and functions for New Forest river site.....	9-13
Figure 9.13	Cross-sectional profile for New Forest canal site showing water and gauge plate levels	9-14
Figure 9.14	Measured and modelled rating data and functions for New Forest canal site	9-14
Figure 9.15	Cross-sectional profile for Dingleydale river site showing water and gauge plate levels	9-15
Figure 9.16	Measured and modelled rating data and functions for Dingleydale river site	9-15
Figure 9.17	Cross-sectional profile for Dingleydale canal site showing water and gauge plate levels	9-16
Figure 9.18	Measured and modelled rating and data functions for Dingleydale canal site....	9-16
Figure 10.1	Snap short of the website home page	10-2
Figure 10.2	Short-term decision- dam releases published on website	10-2
Figure 10.3	Medium-term decision- dam storage probability projections published on website	10-2

LIST OF TABLES

Table 5.1	Projection allocations from Inyaka Dam (WPD-94)	5-1
Table 5.2	Afforestation and estimated streamflow reduction (DWAf 2009a).....	5-2
Table 5.3	Raw water abstractions for the Water Treatment Works managed by Bushbuckridge municipality.....	5-3
Table 5.4	Annual raw water abstractions in 2010 for Water Treatment Works managed by BRR Water Board	5-3
Table 5.5	Monthly raw water abstractions for the Water Treatment Works managed by Bushbuckridge Water Board (BBWB) in m ³ /month.....	5-4
Table 5.6	Monthly raw water abstractions for the Water Treatment Works managed by Mbombela Municipality in m ³ /month	5-5
Table 5.7	Current irrigation water requirements in 2010.....	5-6
Table 5.8	Location of irrigation pumps for Hoxane and Saringwa irrigation schemes	5-8
Table 5.9	Pump abstraction capacities.....	5-9
Table 5.10	Summary of current water requirements per sector (2010).....	5-9
Table 6.1	List of dams and their characteristics	6-1
Table 6.2	Abstraction weirs in the Sand River catchment.....	6-5
Table 6.3	The flow release rules.....	6-7
Table 6.4	Water Treatment Works in Sabie-Sand catchment	6-10

Table 6.5	Irrigation schemes in Sand River sub-catchment.....	6-11
Table 9.1	List of real time rainfall stations in the Sabie-Sand catchment.....	9-5
Table 9.2	List of real time flow gauges in the Sabie-Sand catchment	9-5
Table 9.3	Hydraulic data (rating) collected.....	9-8
Table 9.4	Surveyed water surface slopes and manning resistance coefficient estimates.....	9-9
Table 9.5	Rating coefficients for Equation 3.1.....	9-10
Table 10.1	Monthly information needs and decisions required.....	10-3
Table 10.2	Weekly information needs and decisions required.....	10-3
Table 10.3	System Operating Forum Members.....	10-4

LIST OF ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit, University of Natal.
BBRLM	Bushbuckridge
BTP	Bosbokrand Transfer Pipeline.
DSS	Decision Support System
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry.
EMC	Ecological Management Class
EWR	Ecological Water Requirement.
GIS	Geographical Information System
ICMA	Inkomati Catchment Management Agency.
IWAAS	Inkomati Water Availability Assessment Study
m.a.s.l.	Mean above sea level
MAP	Mean Annual Precipitation.
MAR	Mean Annual Runoff.
NWA	National Water Act (Act No. 36 of 1998).
RISKOMAN	Risk-based operational water management for the Incomati River Basin
SAWS	South African Weather Service
TPTC	Tripartite Permanent Technical Committee
WAS	Water Administration System.
WATPLAN	Operational Monitoring Product for Planning and Water Allocation in the International Incomati Basin
WMA	Water Management Area.
WRC	Water Research Commission
WREMP	Water Resources Modelling Platform
WRPM	Water Resources Planning Model
WSS	Water supply services

1 INTRODUCTION

Water resources in South Africa have reached high levels of stress in almost every catchment. In addition water resources management and operational challenges have changed extensively with time as have social, political and economic objectives, water management goals and technological aspects. International and ecological flow requirements have the highest priority of supply in terms of the National Water Act (Act 56 of 1998). Sustainable use and management of scarce water resources has become impossible without the establishment of a flexible and adaptable operational Decision Support System (DSS) for the river systems. The Sabie-Sand River System is one of the river systems where such DSS is required.

The Sabie River and its main tributary, the Sand River, are located upstream of the Kruger National Park, which has high ecological flow requirements (**Figure 1.1**). This important factor, coupled with rural development and improved service delivery to the rural sector, necessitated the construction of the Inyaka Dam which was completed in 2000. The dam was constructed in the Marite River, which is located in the Sabie River catchment in the X3 drainage region of the Inkomati Water Management Area adjacent to the Sand and Mac Mac rivers. The catchment area of the dam covers 210km², mainly in the Graskop vicinity. At this time, detailed operating rules to meet the ecological Reserve as well as other water requirements within these catchments were developed by the Department of Water Affairs and Forestry (DWA, 2003). These operating rules were never implemented. It seems that the main reason for this was that the Sabie catchment was not unduly stressed and therefore there was not much pressure on the Department of Water Affairs (DWA) to implement the operating rules. This situation has now changed. The final phase of the Inyaka Water Treatment Plant in Bushbuckridge (which treats water from the Inyaka Dam) will be completed shortly hence maximizing demand in the system. Mbombela Municipality also wants to transfer more water from Sabie River to Nsikazi North. The Sabie-Sand Game Reserve has threatened to take legal action if steps are not taken to implement the ecological Reserve in the Sand River catchment. The result is that the system as a whole is likely to become water stressed in the near future. Improved operation is imperative if all water requirements, including the Reserve, are to be met.

SPECIFIC OBJECTIVES

The specific objectives of the study were to:

- Review the current findings of the relevant water resources studies as well as relevant supporting studies in the area. This entailed assessing the existing operating rules and updating them taking new information into account such as updated hydrology, updated ecological requirements and updated water use requirements.
- Develop and install the necessary monitoring systems in the catchment to track water uses allocated and utilised by all water users each hydrological year.
- Update all existing decision support models in the catchment and integrate them in an operational framework.
- Implement an Annual allocation model for the annual allocation of monthly abstractions which should include forecasting of hydrology and the updating of this information each quarter in any hydrological year if conditions are shown to have changed from what was estimated at the start of hydrological year.
- Implement a water allocation and distribution management system to be used to track the water use allocations made and utilised (abstracted) by all users for each hydrological year.
- Set up a real time operating decision support system for the Sabie-Sand River System. This system will be updated on regular basis with all available flow and water use information on the system.
- Identify necessary rain and evaporation gauges which require updating to a real time format.
- Identify suitable control points in the rivers which need to be updated to provide real time flow data.
- Integrate the real time system with forecasting system which enables water managers to make decisions about impending water releases and water use strategies.
- Compute the probability of various reservoir trajectories using stochastic hydrology. This entails developing benchmarks for different curtailment levels in the system and investigates the best run-of-river and reservoir allocation method to be used for efficient real time operations.
- Refine the ecological Reserve and optimise the water use with regard to releases for the Reserve.
- Investigate the requirements for on-going maintenance and support for the models developed (including data requirements).
- Provide training and management support to DWA and ICMA operating managers.

2 SCOPE OF WORK

The scope of work for developing a real-time DSS involved the following tasks:

- Obtain estimates of current day water use within the system and establish a water allocation database.
- Establish the location and capacity of all abstractions and diversion works within the system.
- Develop hydrological model to forecast the probable river flows based on antecedent conditions in the catchment.
- Develop an annual allocation model for the annual allocation of monthly abstractions.
- To quantify the required releases to meet the required allocations and Reserve using short term allocation model.
- Hold stakeholder meetings to disseminate knowledge of the system and obtain buy-in from users in the system.
- Provide technical and managerial support to DWA and ICMA operational staff during the course of the study.
- Provide training on the DSS as well as training and operating manuals.

The over-arching approach to this study involved a review of the work which has already been done in developing operating rules for the Sabie-Sand and to improve on these where necessary. Hence the overall approach to the study involved:

- Utilising the Water Administration System for the day to day management of the system.
- Utilising the Sellick/Bonthuys (later enhanced by Mallory, Gerber and Cai as part of the Crocodile East Operating rules) approach for carrying out probabilistic analyses to forecast river flows. These methods are documented in DWAF, 2003 and Mallory et al, 2009.
- Utilising the Water Resources Modelling Platform (Mallory et al, 2011) for the annual allocations (as an improvement on the Bonthuys Dos-based model, DWAF, 2003).
- Utilising the Water Research Commission (WRC) rainfall-runoff software of Mallory and Sawunyama (2012) to estimate tributary flows using forecasted rainfall (details are given in Section 4.2).
- Developing a website through which information will be made available to users in the system.

In the Sabie River sub-catchment, management decisions are largely based on recent, present and future weather conditions, river flow and reservoir storage and are supported by the annual allocation model, the river flow management model and the ecological reserve estimation model. As such, real time data on river flows and certain key water abstractions within the system are required to support the use of these decision support models (**Figure 2.1**).

In the case of the Sand River sub-catchment, besides the management of the water entitlements; there cannot be active management of the river flow and the water resources, except on a local scale where users are supplied from dams. As a result, the river flow, and therefore the ecological Reserve, should be managed in a passive manner by limiting the irrigation abstractions from the rivers to a proportion of the available flow at the abstraction points (**Figure 2.2**) Thus, domestic water uses would be estimated from records of pump capacities and pump durations. Where domestic users are supplied directly from the water resources of the Sand River sub-catchment,

they must be compensated for by releases from the Bosbokrand Transfer Pipeline (BTP) into the Sand River sub-catchment to ensure that the ecological Reserve is not reduced at site near Exeter.

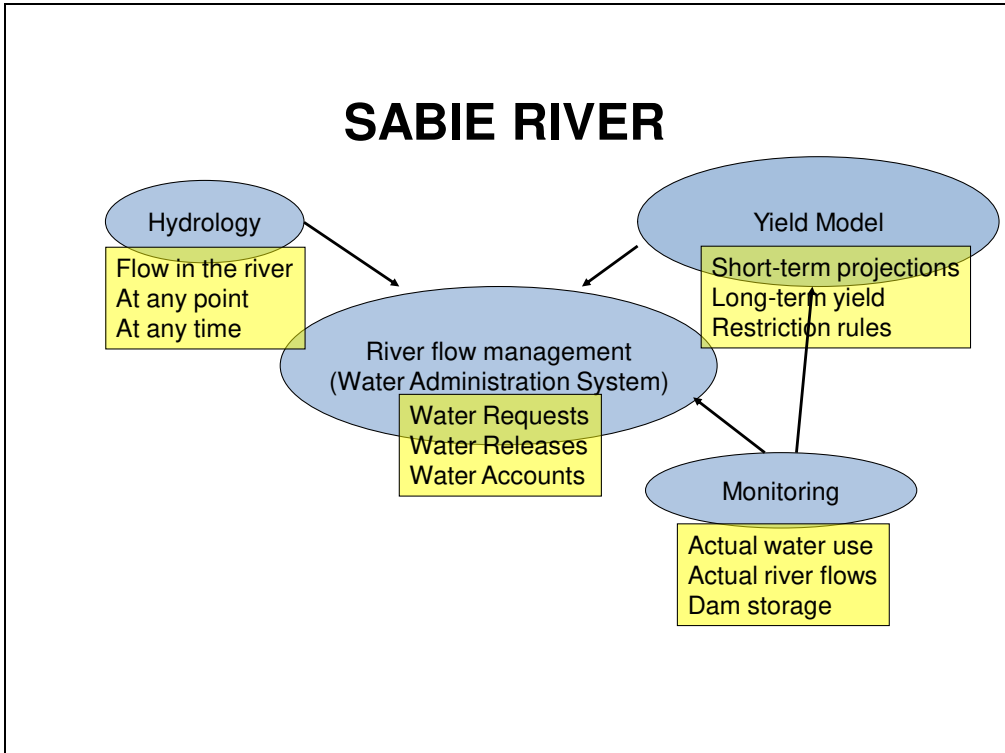


Figure 2.1 River flow management using Water Administration System

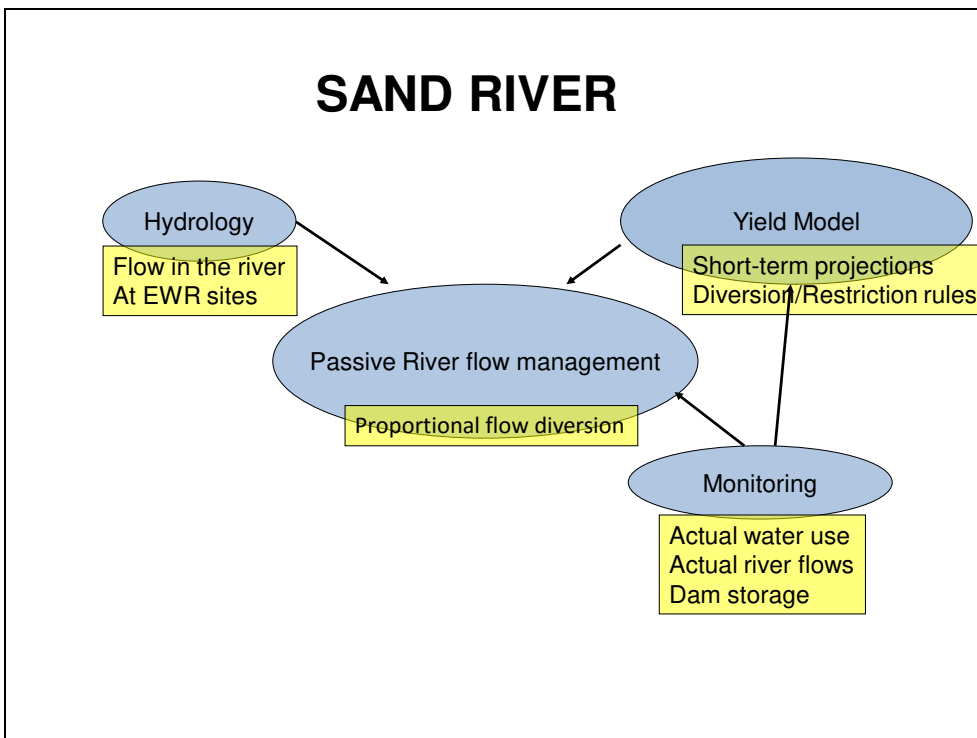


Figure 2.2 Passive river flow management

3 DESCRIPTION OF STUDY AREA

The Sabie River is a major tributary of the Inkomati River within Inkomati Water Management Area in South Africa. The Sand River and the Marite River are major tributaries of the Sabie River as shown in **Figure 1.1**.

3.1 CLIMATE

The Sabie River catchment essentially falls within the Mpumalanga Lowveld climatic region, which generally has a warm to hot sub-tropical climate. The climatic conditions are closely associated with the topography and a somewhat cooler climate prevails along the escarpment formed by the Drakensberg Mountains in the west. The entire Sabie River catchment is prone to tropical cyclonic storms. In the Lowveld region of the catchment the mean annual precipitation (MAP) is about 600 mm on average. Towards the Drakensberg mountains in the upper Middleveld region the rainfall increases rapidly with altitude and the MAP reaches 2 000 mm in the west. The rainy season generally lasts from about November to March, with the maximum rainfall usually occurring in January. The mean annual gross Symon's Pan evaporation varies from about 1 700 mm in the east to about 1 400 mm in the west. During the summer months the average gross evaporation is about 40% higher than during the winter months in the Middleveld region and about 60% higher in the Lowveld region (DWAF, 2003). Maximum air temperatures and ranges in temperature show some inverse correlations with altitude.

3.2 TOPOGRAPHY

The Sabie River rises in the west of the catchment in the Drakensberg mountains north of the Long Tom Pass at an altitude of about 2 200 m.a.s.l., while the Sand River also rises in the Drakensberg mountains to the north east in the Blyderivierpoort Nature Reserve at an altitude of about 1 500 m.a.s.l (DWAF, 2003). The altitude at the confluence between Sand River and Sabie River is 225 mean above seal level (m.a.s.l). At the border with Mozambique the bed of the Sabie River is at an altitude of approximately 110 m.a.s.l. The distinct topographical features of the Sabie River catchment have been used to subdivide the catchment into two topographical regions viz. the Middleveld and the Lowveld regions, for ease of reference. The 600 m.a.s.l. has been selected as broadly forming the boundary between the two regions (DWAF, 1994).

3.3 GEOLOGY AND SOILS

The Sabie River catchment is occupied by three major lithostratigraphic units. These are the Transvaal Sequence in the west, the Basement Complex in the centre, and the Karoo Sequence in the east. More details can be found in the report on the development of operating rules for Sabie River (DWAF, 2003). The residual soil profiles of the rocks of the Basement Complex display distinctly different engineering properties in the areas that generally correspond to the Lowveld and the Middleveld regions. The Middleveld region generally coincides with the (old) African erosion surface and the residual soils are generally very thick and are highly leached, resulting in a low density and potentially collapsing fabric. The Lowveld region generally coincides with the post-

African erosion surface and the residual soils are much thinner and of higher density and have an almost negligible collapse potential compared with the soils in the Middleveld region. A wide variety of transported and residual soils derived from the rocks that occupy the Sabie River catchment are found in the catchment. The erosion resistance of most of the soils in the Sabie River catchment is relatively high and consequently sediment yields are also relatively low.

3.4 VEGETATION

The natural veld types consist of North-eastern Mountain Sourveld and Lowveld Sour Bushveld of the inland tropical forest types in the western portion of the Sabie River catchment, and occupy most of the Middleveld region, while Lowveld and some Arid Lowveld of the tropical bush and savannah types occupy the Lowveld region of the catchment in the east. Large portions of the Sabie River catchment are occupied by the Kruger National Park and the Sabie Sand Game Reserve. These two nature reserves contain large numbers of indigenous fauna (DAAF, 2003).

4 HYDROLOGY

4.1 NATURAL HYDROLOGY

The natural hydrology used in the annual allocation model was based on the IWAAS study (DWAF, 2009a) and the present day hydrology was updated based on 2011 water requirements (Section 5).

4.2 REAL TIME HYDROLOGY

4.2.1 Introduction

Real-time modelling of any catchment requires estimates of inflow where these are not measured. There are two solutions to this problem. The one solution is to extrapolate measured flow at one point in the catchment to other points assuming the flow at the ungauged points is at the same point on the flow duration curve as the observed flow. This is the method that was used in the original Sabie-Sand real-time model setup as part the DWAF Sabie Operating Rules (DWAF, 2003). The advantage of this method is that it is relatively simple to implement. The disadvantage is that it does not take into account the variability of rainfall in the catchment.

The alternative method is to use a rainfall-runoff model to estimate the runoff in all sub-catchments that are not gauged. The challenges in setting up a rainfall-runoff model for real time applications are firstly that the model must be able to accept the antecedent conditions of the catchment as this has a significant influence on the catchment's response to a rainfall event. Secondly, there must be sufficient observed flow to calibrate the rainfall/runoff model. The third challenge is that there must be sufficient real-time rainfall gauges in the catchment under consideration.

In previous real-time operational projects the above three challenges could not all be overcome. There are seldom sufficient rainfall gauges in South African catchments to drive a real-time rainfall-runoff model. Secondly, until recently, readily available hydrological models were not structured to accept antecedent catchment conditions. In the Sabie-Sand real-time operation project these challenges were largely overcome by developing a rainfall/runoff model tailored to real-time applications. This report describes this rainfall/runoff model and its application in the Sabie-Sand catchment.

4.2.2 Theory of rainfall-runoff process

4.2.2.1 General Principles

The relationship between rainfall and runoff is highly complex and non-linear. There are numerous factors affecting this relationship and in order to model the process accurately requires a vast amount of information, for example, rainfall, soil properties, slope, water use in the catchment, etc. However, the process can be simplified as follows:

Rainfall is adding water to the catchment while a combination of runoff and evaporation are removing water from the catchment. Water is only added to the catchment when it rains but only a small fraction of the rainfall is observed as surface runoff. Much of the rainfall is evaporated back

into the atmosphere while a small portion infiltrates into the soil to produce a delayed response to rainfall.

Runoff is not immediate but follows two distinct processes:

- Immediate runoff response to a rainfall event
- Delayed response to a rainfall event.

The model developed for the Sabie-Sand catchment is essentially a 'black-box' model in that there is only a limited attempt to link the processes involved to actual physical data. The model needs to be calibrated to fit observed flow. Nevertheless, the various processes that are modelled are real but a complete understanding of the processes is not required for successful modelling. The processes included in this model are:

- Runoff response following a rainfall event
- The rapid decline in runoff after rainfall has ceased
- The slower decline in runoff during long periods of no rainfall

These processes are shown on a typical hydrograph in **Figure 4.1**.

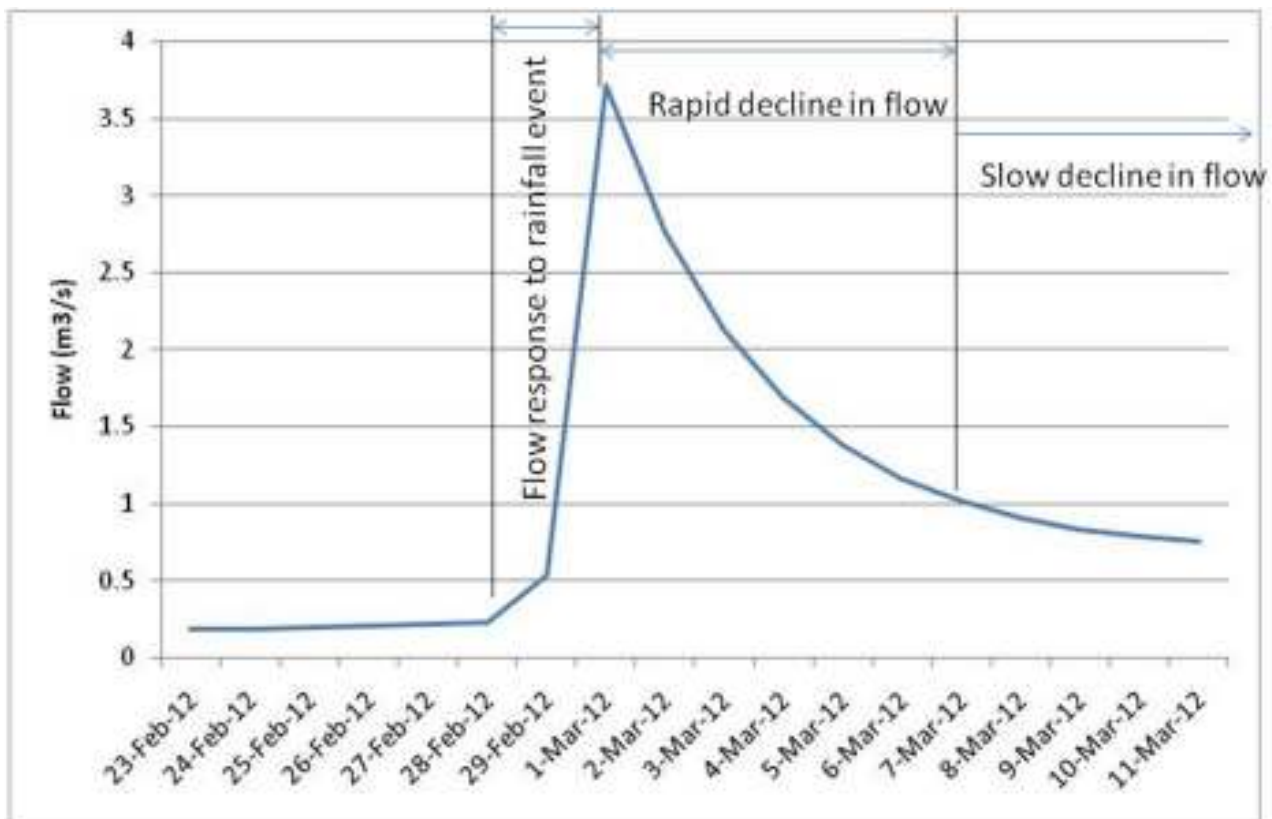


Figure 4.1 Rainfall-runoff processes

4.2.2.2 FLOW RESPONSE TO RAINFALL EVENT

Below a certain threshold of rainfall intensity (based on daily rainfall) there is no runoff due to interception losses, evaporation losses from the surface, pooling on the surface and infiltration into the soil. This threshold can be estimated by plotting rainfall versus the incremental runoff generated by that event.

The immediate runoff generated by a rainfall event, often referred to as storm flow, needs to take into account the antecedent condition of the catchment. In other words, if the soil is already moist from a previous rainfall event then the runoff response will be greater. While other hydrology models keep track of soil moisture within their modelling sub-routines, the principle applied here is that the flow in the river is a proxy of the antecedent condition of the catchment. In other words, if there is already a high flow in the river then the soil moisture must be high, while if the flow is low the soil moisture is low. In order to determine this relationship between rainfall and immediate runoff, only rainfall events that result in **increased runoff** were considered.

Incremental **immediate runoff** is determined by the following equation:

If rainfall > 0 then

$$\text{DeltaRO} = (\text{RO}_{i-1} - \text{RO}_i) \dots \dots \dots \text{Equation 1}$$

Where:

DeltaRO is the increase in runoff over the relevant time step (in this case 1 day)

RO_i is the runoff on the day under consideration

RO_{i-1} is the runoff on the previous day

If DeltaRO is less than zero then DeltaRO is set to zero. This results in a plot such as that shown in **Figure 4.2**. A power function can easily be determined for this relationship.

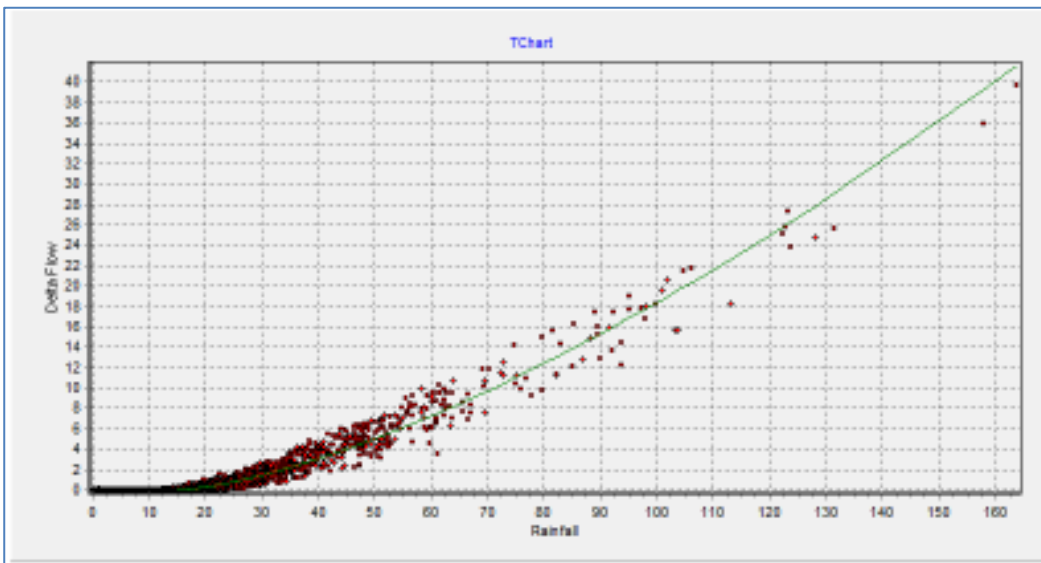


Figure 4.2 Incremental runoff response due to a rainfall event

The function used in this model is:

$$\text{DeltaRO}_i = C1 \times (\text{Rainfall} - \text{Threshold1})^{\text{power1}} \dots \dots \dots \text{Equation 2}$$

Where:

C1 and *Power1* are constants which need to be determined through calibration Threshold 1 is the minimum rainfall (in mm) required to result in an increase in runoff from the catchment.

4.2.2.3 DECLINE IN RUNOFF AFTER A RAINFALL EVENT

Once rainfall ceases runoff will decline over a period of time. The rate of decline depends on many factors, such as the size and slope of the catchment and the volume of water stored in the catchment's soil and groundwater. The delayed response to a rainfall event has two components. A rapid reduction in flow overland and reduction in interflow, and a much longer delayed flow reduction, which is generally accepted as being supplied from groundwater although could also be source from deep soil moisture in catchments with deep soil.

Equations for the two responses (rapid and slow), are described in the following sections.

RAPID RESPONSE

The rapid recession relationship is a function of the size and slope of the catchment with surface runoff from large flat catchments taking place over a longer time period than small steep catchments. The magnitude of the rainfall event also plays a role in that large rainfall events take longer to drain off the surface than small rainfall events. Several rapid runoff responses are plotted in **Figure 4.2** to demonstrate this point.

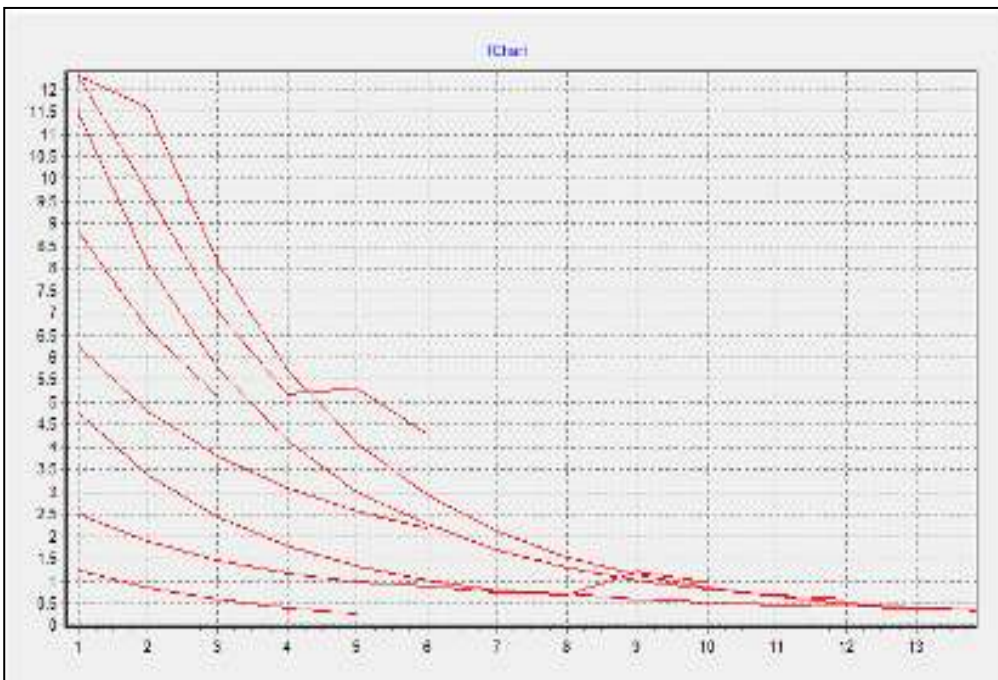


Figure 4.3 Samples of rapid decline in runoff following a runoff event

The curves shown in **Figure 4.3** all follow a similar pattern to which an equation can be fitted. The form of this equation is:

$$RO_i = RO_{i-1} \times \text{Flood recession factor} \dots \dots \dots \text{Equation 3}$$

SLOW RESPONSE

The slowly receding flow, often referred to as baseflow, has been modelled by assuming that groundwater/soil moisture is stored in a reservoir from which water flows out slowly over time with

maximum and minimum flow constraints set by observation. The following equation is used to model this process:

$$Baseflow_i = GWStorage_i / BFI \dots\dots\dots Equation 4$$

Where:

GW Storage = Groundwater storage in million m³

BFI = Baseflow index which is a constant determined through observed flow and calibration

Groundwater storage is calculated as follows:

$$GWStorage_i = GWStorage_{i-1} - Baseflow_i + Recharge_i \dots\dots\dots Equation 5$$

Groundwater recharge has been assumed to be a percentage of the rainfall above certain threshold. This threshold and the recharge rate is difficult to estimate in practice but can be determined by assuming that there is a groundwater balance over the long term. In other words, the assumption is made that in a perennial river system, if rivers are still flowing after long periods with no rain, then the groundwater storage has not been depleted, and similarly, in non-perennial systems clearly the groundwater store available to supply baseflow does become depleted occasionally.

The parameters of the groundwater recharge model can easily be determined through trial and error calibration. The following groundwater parameters need to be determined:

- Rainfall Recharge threshold: Rainfall above which recharge occurs
- Groundwater maximum storage available
- Maximum baseflow (from observation)
- Minimum baseflow (from observation)

The parameters are determined by trial and error or the process below, which gives some physical meaning to the selected parameters.

The procedure for estimating groundwater parameters is as follows:

- a. Select the longest period with no or insignificant rainfall. The discharge over this period is assumed to be from groundwater or deep soil and the source of slow response flow. From this the groundwater storage available can be determined by summing the flow during this period.

$$Qtot(base) = \sum_{i \text{ to } j} Q_i \dots\dots\dots Equation 6$$

Assume that the ground water/soil moisture storage at the start of this period is the total flow storage discharged over this period, i.e.

$$GWst_{max} = Qtot(base) \dots\dots\dots Equation 7$$

- b. The Baseflow Index (BFI) can now be determined from the flow rate at the start of the selected period, defined here as Q_i

$$BFI=Q_{tot}(base)/Q_i.....Equation 8$$

A difficulty with the black-box approach adopted in the development for this real-time hydrology model is trying to ascertain at which point the rapid runoff response has ceased and the slower base flow response takes over. An equation cited in the literature suggests that the duration of the rapid response is a function of the size of the catchment, that is

$$D = 0.827 A^{0.2}Equation 9$$

This equation is probably an over-simplification and has not been used in this model.

The approach taken in this model is to recognise that there is no particular point at which one process stops and the other commence. Both processes are continuous. The procedure adopted is to continuously model discharge from groundwater and from overland flow/interflow, the total flow in the river being the sum of these two flows. The reasoning being this approach is that groundwater discharge will always occur provided there is water in groundwater storage and a head difference to drive the flow. Surface runoff and interflow, on the other hand, will taper off after a few days but approaches zero asymptotically and does not suddenly stop after a set time period. The principle is demonstrated in **Figure 4.4** which shows the baseflow and surface runoff components as well as the total flow, which is the sum of these two.

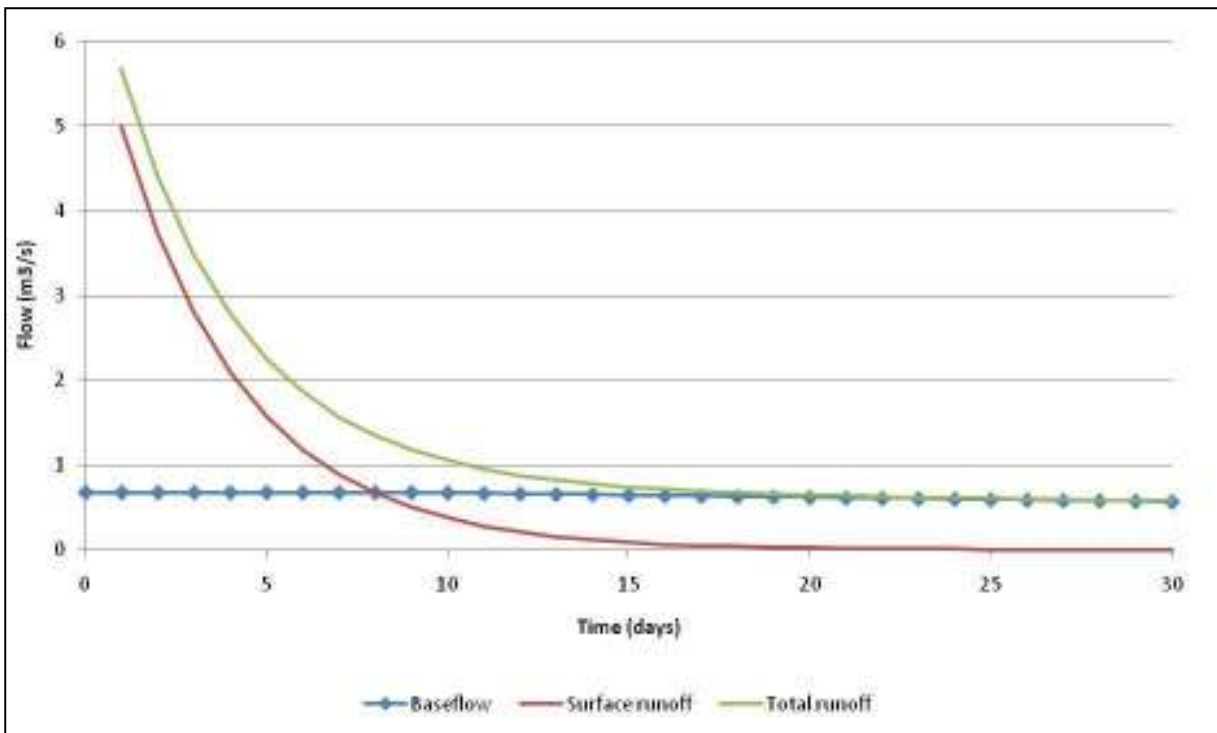


Figure 4.4 Combining surface runoff and baseflow

Figure 4.4 shows that surface runoff continues for some time but becomes negligible after about 20 days and can be ignored after that. Baseflow, on the other hand, reduces much more slowly and in

the case of the Sabie River catchment continues right through winter. This is probably due to the large sub-surface storage created by the dolomites in the upper catchment.

4.2.3 Model calibration

Calibration of any hydrological model is problematical due to the spatial variability of the rainfall and the limited number of flow gauges. The spatial variability of rainfall is an especially significant problem in the Sabie-Sand catchment where the highest rainfall falls on the escarpment and is often not recorded due to a lack of rainfall gauges. ICMA through RISKOMAN and WATPLAN projects installed 5 real time rainfall gauges in 2012 that are now used to improve rainfall estimation. A Theissen polygon approach was used to derive spatial rainfall for each key tributary in the Sabie and Sand River catchments.

4.3 SABIE-SAND DAILY MODELLING APPROACH

The approach taken in the Sabie-Sand River catchment was to maximise the use of available data, as listed below:

- Pitman-based monthly hydrology as updated during the course of the Inkomati Water Availability Assessment (IWAAS) (DWAF, 2009)
- While monthly hydrological model suffer similar calibration challenges to that of daily models, the monthly hydrology documented in the IWAAS study is the accepted standard and have been used as the basis of determining the available water resources and hence is used to assess water use licence. It is important therefore that the daily hydrology model should not deviate from this understanding derived from the IWAAS study.
- The ACRU model (Smithers et al, 1995) has been set up for the whole of the Inkomati catchment, and while this set of natural daily flow time series does not necessarily reflect the same water resources availability as the IWAAS study, it does give a good indication of the variability of flow at a daily time step.
- A recently completed WRC study (Mallory and Sawunyama, 2012) used ACRU daily flow time series to disaggregate monthly flows into a statistically plausible daily flows which maintain the statistics of the monthly flows.

The approach used in the Sabie-Sand river catchment was therefore as follows:

- Use the WRC Daily model (Mallory and Sawunyama, 2012) to disaggregate the IWAAS monthly hydrological time series into daily flows (at quinary scale).
- Calibrate the Sabie-Sand daily real-time hydrological model against the WRC Daily flow time series.

5 WATER REQUIREMENTS

The water requirements for Sabie-Sand catchment were first updated in 2004 through the IWAAS study (DWAf 2009a). In 2010, when the present study commenced, the water use information that required updating was the domestic (Section 5.1) and irrigation water use (Section 5.2). Forestry and industrial use have not changed since 2004.

Investigations at the time on constructing Inyaka Dam suggested that the Inyaka Dam would increase the net yield of the Sabie and Sand catchments by a total of 57.8 million m³/annum (16.6 million m³/annum of which would be available only at low assurance). The increased yield in the system would have addressed projected water shortages in both the Sabie and Sand River catchments, with the BTP allowing transfer of up to 25 million m³ per annum from Inyaka into the Sand sub-catchment. Projected allocations were indicated in the Inyaka Dam White Paper (WP D-94) as follows:

Table 5.1 Projected allocations from Inyaka Dam (WPD-94)

High Assurance Supplies:	Million m³/a
Water for primary use in the Sand River Catchment	18.1
Water for primary use in the Sabie River Catchment	14
Water for augmenting the low flow of the Sand River	4.1
Water for augmenting the low flow of the Sabie River	5
Low Assurance Supplies:	
Irrigation of 280ha in the Sand River Catchment	2.9
Irrigation of 1,480ha in the Sabie River Catchment	13.7
Total	57.8

At the time of drafting the White Paper it was estimated that the above allocations would meet projected domestic requirements until at least 2010 and would allow expansion of irrigation in both the Sabie and Sand Catchments, and also provide a quantity of water (9.1 million m³/a) to meet what is currently referred to as the ecological Reserve.

Current hydrological assessments for the whole Sabie system suggest it is already fully allocated. The reduced availability of water and water shortages is not evident in the system at present, because, despite being fully allocated, the system is not fully utilised. The distinction between being fully allocated and fully utilised is important.

Firstly, the Reserve requirements are not currently being fully met. Secondly, the bulk supply line linking parts of Bushbuckridge directly to Inyaka Water Treatment Works has not been completed to date and, of the originally intended transfer of **25** million m³/annum into the Sand sub-catchment, only about **13** million is actually being abstracted at present. Water that will in future be pumped across the Sand River and currently it remains in the Sabie sub-catchment and appears,

incorrectly, to be available for use elsewhere. Lastly, extensive irrigation schemes exist, both private and state-owned, both in the Sabie and the Sand River sub-catchments, which are not utilizing their lawful allocations at present. Such unused water allocations then become available for downstream use by others (which may include domestic users, irrigators or the Reserve). Existing water legislation allows such water use entitlements to be transferred to other users, but interception and abstraction of unused water without legal entitlement may result in conflict and critical water shortages should such water allocations be re-instated in future. The revitalising of irrigation schemes along the Sabie River at Hoxane and Saringwa is a case in point.

The estimated forestry and streamflow reduction are as presented in **Table 5.1** while there are no significant industry activities except sawmills upstream of Sabie River that they impact on water quality.

Table 5.2 Afforestation and estimated streamflow reduction (DWAf 2009a)

Catchment	Afforestation area (km ²)	Streamflow reduction (million m ³ /annum)
X31: Sabie	797	86
X32: Sand	56	4
X33: Lower Sabie	0	0
Total	853	90

5.1 DOMESTIC WATER USE

5.1.1 Actual water use

The western/upper part of the Sabie Catchment is relatively sparsely settled but the lower/eastern part is characterized by a large number of formal or semi-formal towns and villages, and the domestic requirement of this area is accordingly increasing. Total (current) water abstraction in the Sabie and Sand sub-catchments managed by BBR local municipality and BRR Water Board are as shown in **Tables 5.3** and **5.4**. Total domestic demand includes relatively trivial volumes, such as a large number of Schedule 1 users in the vicinity of Da Gama Dam or in the afforested upper areas of the catchment, but it also includes significant volumes, especially the current abstractions from Inyaka Dam or from the Sabie River. Part of the 13 million m³/annum currently being abstracted from Inyaka Dam provides water to users in the Sabie (e.g. to Maviljan or parts of Bushbuckridge town; i.e. users which lie on the Sabie side of the watershed). However, most of the water is transferred across the watershed to the Sand River catchment where the southern part of the Sand Catchment is supplied up to Dwarsloop, Agincourt and Xanthia (DWA, 2011). The current annual transfers from Inyaka to Sand River catchment is 13 million m³/annum while transfer from Nyongane pump station (Sabie River) to Crocodile River catchment is 6 million m³/annum. There is also a current upgrade of the Hoxane scheme to allow a total of 21 million m³/annum to be transferred to Crocodile River catchment. **Figure 5.1** indicates that Inyaka Dam is not yet fully utilised due to the incomplete BTP transfer to Sand River catchment. While annual allocations are required for annual allocation model, the river flow management model requires water use on monthly basis. This data is presented in **Table 5.5**. **Table 5.6** shows the monthly abstraction patterns for the water treatment works in the Sabie-River catchment and it is clear that with the completion of upgrade of Inyaka Water Works there will be a water shortage in the system.

Table 5.3 Raw water abstractions for the Water Treatment Works managed by Bushbuckridge municipality

Plant :	River :	Period :	Raw Abstracted : m ³
Cork	Sabie	2010/09-2010/11	65653
Marite	Nwaritshi	2010/07-2010/11	524066
Thorndale	Trib. Of sand.	2010/07-2010/11	5328
Dingledale	Canal	2010/01-2010/06	20412
Zoeknog	Mutlumuvi	2010/07-2010/09	99645
Sigagule	Klein sand	2010/07-2010/11	85095

Table 5.4 Annual raw water abstractions in 2010 for Water Treatment Works managed by BRR Water Board

Plant	Water source	Quat	Period	Raw water abstraction (m ³ /annum)	Clear water production (m ³ /annum)
Hoxane	Sabie	X31k	2009/07-2010/06	8400171	8106042
Injaka	Injaka Dam (Marite)	X31k	2009/07-2010/06	12995217	12415171
Shatale	Nwarhele, trib. Of Mutlumuvi	X32e	2009/07-2010/06	691067	549933
Sand river	Mwandlamuhari	X32c	2009/07-2010/06	286829	265842
Edinburgh a	Edinburgh canal	X32c	2009/07-2010/06	522558	299604
Edinburgh b	Edinburgh canal	X32c	2009/07-2010/06	469633	240596
Acornhoek	Acornhoek dam + champagne (Kleinsand) weir	X32c	2009/07-2010/06	1614821	1429888
Dwarsloop	Nwarhele, trib. Of mutlumuvi	X32f	2009/07-2010/06	206225	99767
Thulamahashe	Mutlumuvi	X32f	2009/07-2010/06	1948,188	1874883
Total abstraction	Sabie system			21395388	20521213
	Sand system			5739321	4760513
	Total			27134708	25281725

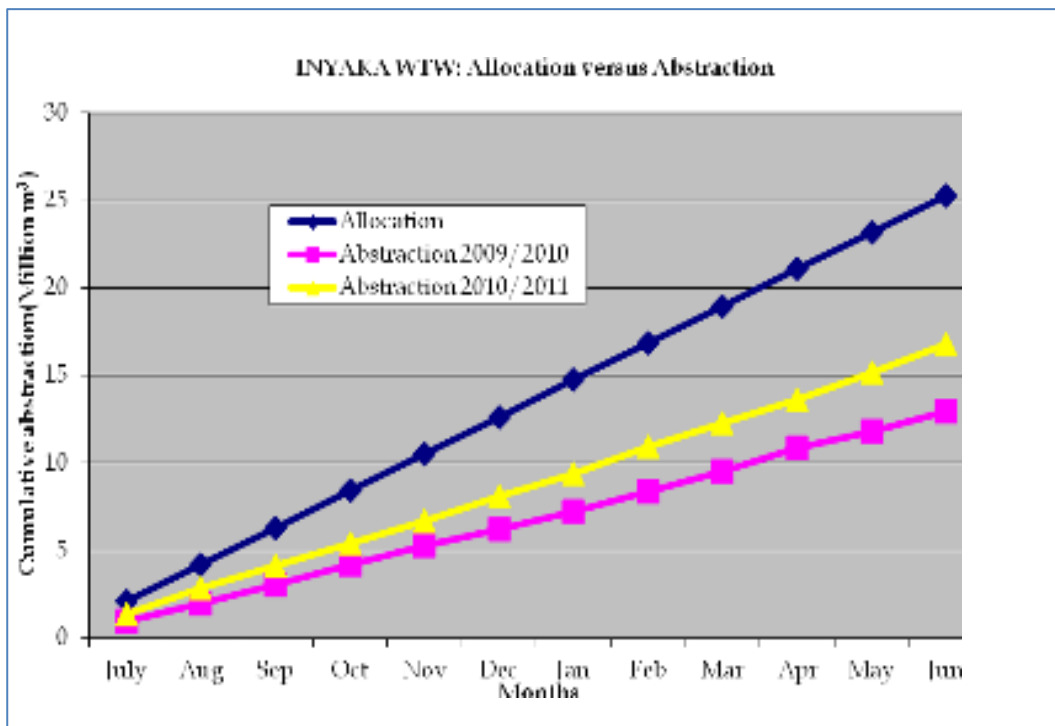


Figure 5.1 Allocation versus actual abstractions at Inyaka WTWs

Table 5.5 Monthly raw water abstractions for the Water Treatment Works managed by Bushbuckridge Water Board (BBWB) in m³/month

Date	Inyaka	Hoxane	Arconhoek	Thulamahashe	Edinburgh A	Edinburgh B	Sand River	Shatale
20/07/2009	948910	678900	129890	131130	60140	39990	22630	59830
20/08/2009	1036020	703080	130510	149110	39990	62000	31310	66960
20/09/2009	1099500	731400	130500	170100	39300	42000	24300	71100
20/10/2009	1115070	683860	120590	169260	44020	42160	18290	63860
20/11/2009	1104900	741300	129600	176700	30000	35400	16200	62700
20/12/2009	934650	694710	117180	179180	40300	36580	27590	62620
20/01/2010	1026720	704630	126790	159650	73780	69440	30690	55180
20/02/2010	1095360	693000	136360	207760	40320	52640	28280	46760
20/03/2010	1153510	647280	168950	157480	40300	40920	22320	47120
20/04/2010	1332000	708300	177300	175200	36300	25500	24300	48600
20/05/2010	995720	713000	125550	109120	42470	7750	23560	52390
20/06/2010	1129200	691800	119400	156000	36600	14700	17100	54300
20/07/2010	1399960	678920	125880	161963	35404	27735	19829	56650
20/08/2010	1460720	677620	135470	158948	35404	11313	15262	53990
20/09/2010	1290300	683760	178040	131390	31847	69823	19877	56660
20/10/2010	1275960	652440	153999	138445	29852	25593	19199	42509
20/11/2010	1279500	699900	171999	115098	33202	68960	26249	42099
20/12/2010	1395930	664670	139500	54690	26629	63887	15120	43600
20/01/2011	1323700	552790	148335	86606	25135	62578	20470	39960
20/02/2011	1486800	644109	157167	2448	23970	62683	27528	46092
20/03/2011	1355320	502987	133280	0	20714	20714	19481	17789
20/04/2011	1395000	562258	98207	0	21085	21085	13341	31017
20/05/2011	1547520	630704	125305	0	25497	25497	27412	40884
20/06/2011	1571100	625590	122910	0	26047	26047	27949	32129

Date	Inyaka	Hoxane	Arconhoek	Thulamahashe	Edinburgh A	Edinburgh B	Sand River	Shatale
20/07/2011	1596050	612720	107855	0	24813	29192	32357	34333
20/08/2011	1475560	672870	156139	1649	22928	25800	20726	44827
20/09/2011	1358580	672170	185920	21851	29590	17861	27900	46080
20/10/2011	1548030	597030	150022	134726	26150	18561	27321	46767
20/11/2011	1369470	597260	137556	164178	31162	21518	29006	48878
20/12/2011	974210	597530	103117	127764	20955	32193	29364	42130
20/01/2012	1394710	626350	172324	177230	23589	25893	28130	48248
20/02/2012	1552670	639320	151813	107310	5085	5124	26556	36669
20/03/2012	1375140	565930	143195	101426	3037	9209	21391	32970
20/04/2012	1514890	658090	137673	164554	0	0	31731	33420
20/05/2012	1516760	652010	126956	142933	0	0	31175	33760
20/06/2012	1615140	660860	157876	191366	0	0	5985	37880

NB: Red colour means the meter is malfunctioning or is out of order

Table 5.6 Monthly raw water abstractions for the Water Treatment Works managed by Mbombela Municipality in m³/month

Date	Hazyview	Nyongane
20/01/2010	8490	539400
20/02/2010	14230	567300
20/03/2010	14650	548700
20/04/2010	2400	620000
20/05/2010	17050	620000
20/06/2010	17050	579700
20/07/2010	18640	589000
20/08/2010	10150	429060
20/09/2010	28180	567300
20/10/2010	41130	492900
20/11/2010	15290	278202
20/12/2010	12080	283250
20/01/2011	12080	170701
20/02/2011	35720	149820
20/03/2011	17920	148941
20/04/2011	6640	126740
20/05/2011	24800	146583
20/06/2011	41300	132398

5.2 IRRIGATION WATER USE

Irrigation in the Sabie-Sand catchment has always been extensive. Four irrigation boards are currently active in the Sabie sub-catchment. The Sabie Irrigation Board diverts water into a canal from the Sabie River, while the White Waters- Burgers Hall and De Rust Irrigation Boards obtain water from Da Gama Dam, either through releases from the dam into a canal (Burgers Hall IB), directly into the Noordsand River for downstream abstraction (De Rust IB), or both (White Waters IB). Extensive irrigation is also taking place from tributaries of the Sabie River, with the Sabane

River and Langespruit (Quaternary X31D) being particularly intensively farmed. These abstractions have a direct influence on municipal abstraction by Bushbuckridge as they lie upstream of significant domestic taking at Hoxane (for Bushbuckridge LM) as well as Nyongane (for domestic provision to Mbombela LM in the Nsikazi North region).

In addition, numerous other irrigation schemes have historically operated in both the Sabie and the Sand River Catchment, although most of these have recently fallen into partial or complete disuse. Some of them remain disused (e.g. Department Agriculture's Irrigation Schemes along the Noordsand River, Coffee Schemes at Inyaka, Waterval, Zoeknag, Citrus Schemes at Allandale or Dumfries), others remain partially active (New Forest or Dingleydale, Lisbon Estates) and others were refurbished (Hoxane and Saringwa).

However, the expansion in irrigation which had been projected prior to the construction of Inyaka Dam has not materialised. In fact, due to the decline in irrigation practices on many properties, agricultural water use has shown a general decrease during recent years. Unused water entitlements become potentially available for trading; although interception of unused water allocations without due legal process may result in future conflict and water resource stress should those water allocations ever become re-instated.

The allocated irrigation water requirement for Sabie-Sand catchment is 98 million m³/annum in terms of the Interim Inkomati Water Use Agreement. Estimated current water requirements are summarised in **Table 5.7** per quinary catchment. These two volumes are not necessarily the same, since a water allocation may be lawful without currently being used. Likewise, a water allocation may be used without being lawful, raising the possibility of future compliance enforcement and forced cessation of water use. In order to implement real time modelling, real time irrigation abstractions are required and thus in Sabie sub-catchment irrigation use will be updated on weekly basis based on information in Tables **5.8** and **5.9**.

Table 5.7 Current irrigation water requirements in 2010

Source/ Scheme	Demand (Mm ³ /a)	Crop area (ha)							
		Banana	Citrus	Veg	Mango	Coffee/ +Maize	Mac./ Liche	Avo.	Scheduling
Sabie River sub-catchment									
Sabie IB: X31B-1	12.41								1261
Sabie : X31D-1	1.62	186.3		5.5	22.3				
Sabane : X31D-2	9.11	811.1	37.19	15.1			230.5	825.9	
Langspruit : X31D-3	8.48	521.5	26.01	15.58	13.5		252.5	559.7	
Maritsane Dam (Wales) :X31E-2				25			190		
*Marite (Injaka) :									

Source/ Scheme	Demand (Mm ³ /a)	Crop area (ha)							
		Banana	Citrus	Veg	Mango	Coffee/ Liche	Mac./ Liche	Avo.	Scheduling
X31E-3									
*Marite (Waterval): X31G-1									
Marite (Sandford): X31G-3	2.1		128.4	7					
White Waters X31H-1									
Da Gama Dam: X31H- 2									60
Burgers Hall IB: X31J-1									1083.1
De Rust IB: X31J-1									168
White waters IB: X31J-1	*13.24								748.7
Noordsand River: X31J- 1	0.55	17		12		8.5	55.3		
Sabie River (Hoxane): X31K-4	4.66			750					
Sabie River (Saringwa): X31M-1			170		130				
Sabie River *(Lisbon): X31M-1	**3.06		133						
Subtotal	58.13								
Sand River sub-catchment									
Dingleydale Canal: X32C-1	4.64			410		410			
Champagne: X32C-2	1.31		235		45				
*Edinburgh Canal (Allandale): X32C-7									
*Edinburgh Canal (Dumfries): X32C-7									
*Edinburgh Canal (Rolle): X32C-7									

Source/ Scheme	Demand (Mm ³ /a)	Crop area (ha)							
		Banana	Citrus	Veg	Mango	Coffee/ Liche	Mac./ Liche	Avo.	Scheduling
New Forest Canal: X32F- 1	3.06			250		250			
Subtotal	9.01								
Gross Total	67.14								

*Defunct Irrigation Schemes

Table 5.8 Location of irrigation pumps for Hoxane and Saringwa irrigation schemes

No	Scheme name	Size	Discharge	Coordinates
1	Seelokwane 1	ETA 65-250	55m ³ /h	S 24°59.191'
		22 KW motor		E 31°17.129'
2	Seelokwane 2	ETA 65-250	55m ³ /h	S 24°59.039'
		22 KW motor		E 31°16.869'
3	Seelokwane 3	ETA 65-250	55m ³ /h	S 24°59.039'
		22 KW motor		E 31°16.869'
4	Seelokwane 4	ETA 65-250	55m ³ /h	S 24°58.885'
		22 KW motor		E 31°16.493'
5	Upper Cork 1	ETA 65-250	55m ³ /h	S 24°58.101'
		37 KW motor		E 31°19.868'
6	Upper Cork 2	ETA 50-200	30m ³ /h	S 24°58.116'
		11 KW motor		E 31°18.654'
7	Lower Cork 1	ETA 65-250	55m ³ /h	S 24°58.168'
		37 KW motor		E 31°18.633'
8	Lower Cork 2	ETA 50-200	30m ³ /h	S 24°58.695'
		11 KW motor		E 31°18.629'
9	Belfast 1	ETA 40-250	15m ³ /h	S 24°57.931'
		11 KW motor		E 31°22.369'
10	Belfast 2	ETA 40-250	15m ³ /h	S 24°58.295'
		11 KW motor		E 31°21.875'
11	Belfast 3	ETA 50-200	30m ³ /h	S 24°58.377'
		11 KW motor		E 31°21.226'
12	Mkuhlu 1	ETA 65-250	55m ³ /h	Not accessed
		37 KW motor		
13	Mkuhlu 2	ETA 65-250	55m ³ /h	S 24°58.748'
		30 KW motor		E 31°16.046'
14	Mkuhlu 3	ETA 50-200	30m ³ /h	S 24°58.793'
		11 KW motor		E 31°16.157'
15	Big Bend 1	ETA 65-250	55m ³ /h	S 25°0.688'

No	Scheme name	Size	Discharge	Coordinates
		30 KW motor		E 31°14.861'
16	Big Bend 2	ETA 65-250	55m ³ /h	S 25°0.440'
		30 KW motor		S 31°14.850'
17	Ten Farm	ETA 50-200	30m ³ /h	S 24°58.118'
		11 KW motor		S 31°18.653'
18	Saringwa	4* 55KW	127m ³ /h	

Table 5.9 Pump abstraction capacities

Scheme	Flow (m ³ /h)	Flow (m ³ /month)	Flow m ³ /annum
Calcutta 1	250	180000	2190000
Calcutta 2	220	158400	1927200
Saringwa	127	91440	1112520
Belfast	60	43200	525600
Cork	200	144000	1752000

The current water requirements are summarised in **Table 5.10**. These are the provisional water requirements estimates used in modelling water availability in the Sabie River pending the water verification study being conducted by ICMA.

Table 5.10 Summary of current water requirements per sector (2010)

Abstraction point	Demand per water use sector (million m ³ /a)		
	Domestic/Industrial	Irrigation	Transfers out
Sabie Catchment	14	58	13 (to Sand via Inyaka Scheme) 6 (to Crocodile via Nyongane Scheme)
Sand Catchment	6	9	
Total	20 ¹	67	19

¹Includes towns outside the area of jurisdiction of BBR Water Board and BBR Local Municipality, for modelling purposes (Mbombela – Sabie and Graskop and Thaba Chweu – Hazyview and Nsikazi)

6 WATER INFRASTRUCTURE

Water related infrastructure in the Sabie-Sand River catchment is mainly dominated by Inyaka Dam in the Marite catchment and Da Gama Dam in the White Waters catchment. There is an extensive system of canals and pipelines distributing water from these sources to irrigators and domestic users within the Sabie and Sand catchments. The Bushbuckridge water supply scheme supplies water from Inyaka Dam to most domestic users within these catchments. Inyaka dam also makes releases to support the ecological Reserve of the lower Sabie catchments. There are numerous farm dams and small dams scattered over the catchment that are used mostly for irrigation, stock and game watering. The main sources of information are reports available from the Regional office of the Department of Water Affairs (Mpumalanga), reports from municipalities, irrigation board and Department of Agriculture. Some of the information was verified through field visits by the study team.

6.1 DAMS AND ABSTRACTION POINTS

6.1.1 Dams

Dams and associated structures are critical elements of the water management system and supply network in the catchment, as they allow for the storage, distribution and the transfer of water to the water scarce parts of the catchment. **Table 6.1** shows a list of major dams in the system and their characteristics.

In the Sabie catchment there are three storage dams, two large dams, Da Gama and Inyaka dams and a small storage dam for irrigation supply, the Maritsane dam. Inyaka Dam on the Marite River was constructed to increase the assurance of supply to domestic users in the Marite and Sand catchments and to the ecological reserve and in particular to help meet the minimum ecological flow requirements of the Kruger National Park. Detailed operating rules were developed for this dam (DWAf, 2003) but were never been fully implemented. For more information refer to the report entitled 'Sabie River Catchment: Operating rules and Decision Support Models of the Management of the Surface Water Resources' (DWAf, 2003).

Da Gama Dam is used mainly for irrigation and is located in the White Waters River tributary catchment. The dam was purchased by the White Waters Irrigation Board who operates the dam to supply water to their members downstream of the dam. The storage in the dam has never dropped below 60% of its full supply capacity (van Dyk, personal communication), from which it can be surmised that this dam is under-utilised. The area-capacity relationships for the Da Gama and Inyaka Dams are shown in **Figures 6.1** and **6.2** respectively.

Table 6.1 List of dams and their characteristics

Dam	FSA(km ²)	FSC (Mm ³)	Power	User category
Acornhoek	0.23	1.80	0.60	Domestic
Casteel	0.16	1.32	0.60	Dingleydale scheme

Dam	FSA(km²)	FSC (Mm³)	Power	User category
Edinburgh	0.60	2.42	0.60	Allendale and Dumfries scheme
Orinoco	0.2	1.62	0.60	New Forest scheme
Inyaka	8.11	125.03	0.65	Domestic and Reserve
Da Gama	1.29	13.58	0.55	White Waters scheme
Maritsane	0.5	2.04	0.60	Wales irrigation

Source: Dam safety database, 2006

In the Sand River water users depend mostly on unregulated flow of the Sand River and its tributaries. There are a few storage dams built in the Sand catchment namely, Casteel, Orinoco, Acornhoek and Edinburgh. The storage capacity of these dams is limited and users in the catchment depend mostly on the unregulated flow.

Acornhoek dam: Water is pumped into this dam from Sand River and after treatment; the water is used for domestic use by the surrounding community and Tintswalo hospital.

Casteel dam: This dam was built in 1965 and the water stored is used to augment the flow in the Tlulanziteka River and is used downstream by Dingleydale canal. Currently the outlet valve and siphon are blocked so no water is released downstream.

Edinburgh dam: This dam was built mainly for Allendale and Dumfries irrigation schemes. The dam discharges water into the main canal and since the schemes are no longer working the canal now supplies Edinburgh A/B treatment works.

Orinoco dam: It is an off storage dam which receives surplus water from Dingleydale and New Forest canals. However, currently no water from Dingleydale canal reaches Orinoco dam because all the water is abstracted.

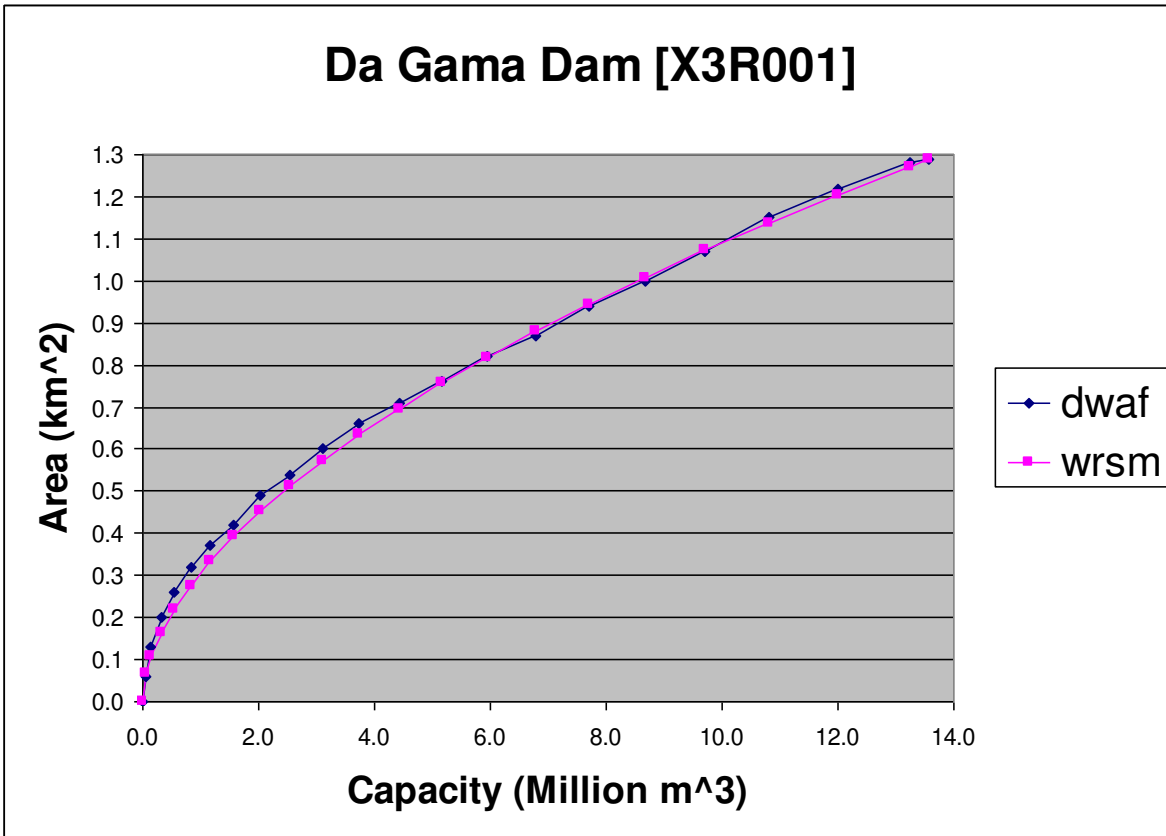


Figure 6.1 Da Gama Dam (X3R001) Area-Capacity relationship (DWAf 2009)

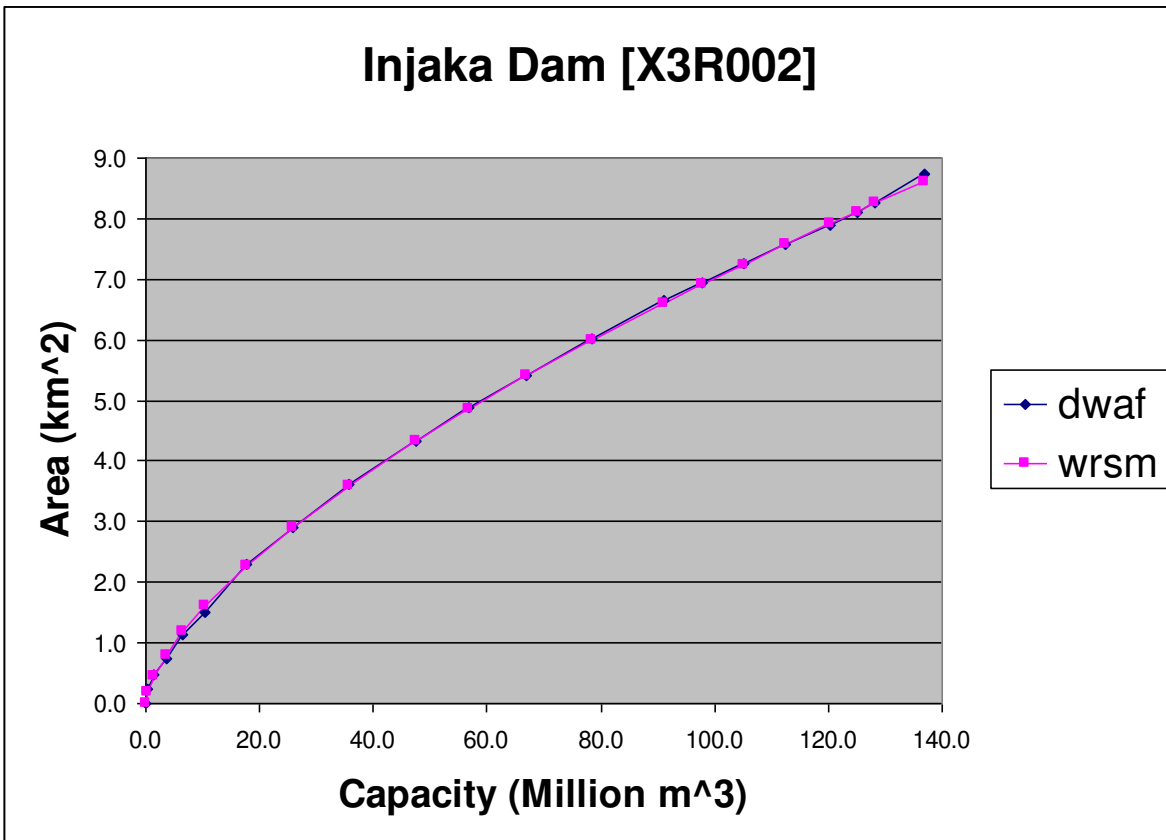


Figure 6.2 Inyaka Dam (X3R002) Area-Capacity relationship (DWAf 2009)

6.1.2 Abstraction points

Figure 6.3 shows a map of abstraction points in the Sabie-Sand River catchment. In the Sabie River the main abstraction points are for the domestic use at Inyaka, Marite, Hazyview, Cork and Nyongane abstraction points. In 2011, the Department of Agriculture installed new abstraction pumps for the Saringwa and Hoxane Irrigation schemes. In the Sand catchment irrigation abstraction is mainly from run off river. The major detriment to equitable distribution of the available water in the Sand catchment has been determined in the Sabie River Operating Rules (DWAf, 2003) and a number of irrigation weirs and canals in the upstream tributaries of the Sand River exist where the water is diverted to provide irrigation to agricultural schemes. **Figure 6.4** shows a schematic layout of the canal systems within the Sand River catchment while **Table 6.2** lists the name of abstraction weirs and their respective locations.



Figure 6.3 Domestic and irrigation pump abstraction points in Sabie-Sand River System

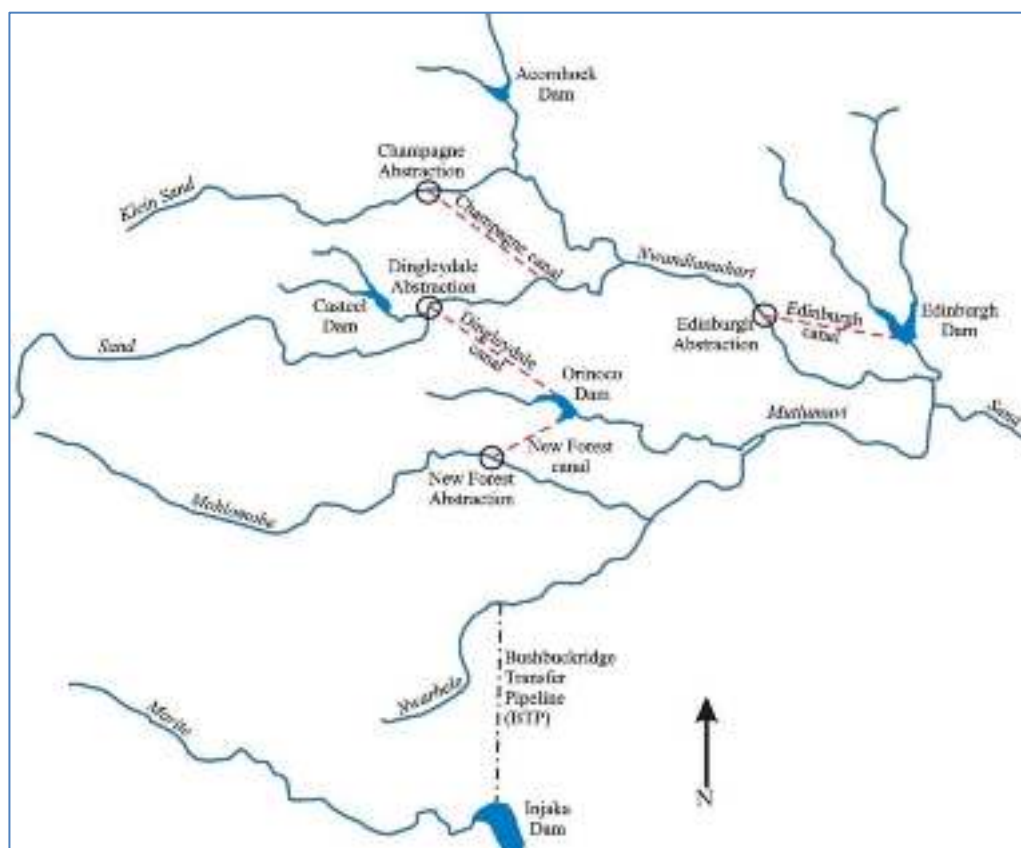


Figure 6.4 Layout of diversion works in the Sand River catchment (Source: DWAf, 2003)

Table 6.2 Abstraction weirs in the Sand River catchment

Name	River	Description
Champagne weir	Klein Sand	Located southwest of Rooiboklaage village. Abstracted water pumped into Acornhoek dam. Supply domestic and irrigation. Canal currently blocked.
Abstraction pumps: Champagne	Klein sand and Tluladziteka	No measuring device on both pumps. Capacity of pump at Tluladziteka is not known while that at Klein sand is 50m ³ /h
Dingleydale weir	Tluladziteka	Located downstream of Casteel dam (approx. 1.5km). Supply water to Dingleydale and Champagne
Edinburgh weir	Mwandlamuhari	Located south of Songeni village. From the weir water is diverted through canal to Edinburgh dam. No longer supply irrigation schemes
New Forest weir	Mutlumuvhi	Sluice gate at the weir broken and this supplies water to New Forest scheme

Champagne Abstraction Weir

Water is channelled from the weir into the circular silt trap where the sluice gate then controls the flow into the canal (currently all the water returns into the river and does not flow into the canal). According to the operating rules, 35% of the river flow should be allowed to flow past the abstraction points down the river. This comes into effect when the river flow drops to a threshold level of 0.195 m³/s (**Table 6.3**). Champagne abstraction is the only abstraction point where some water is released downstream. The reason for this is because the flow into the canal is reduced by another sluice gate to allow water to overflow at the weir into an inlet where water is pumped to Acornhoek dam. Treated water from the dam supplies the domestic needs of Acornhoek, Tintswalu hospital and surrounding settlements. At this site, the combination of both the domestic abstraction and the irrigation abstraction from the weir must allow 35% of the river flow to flow past the weir and down the river.

Dingleydale Abstraction Weir

The design of this weir is such that there is currently no provision made for a release flow back into the river and all the water is channelled towards the canal. The sluice gates at the overflow are jammed closed and out of order thus only allowing a small percentage of the flow to return downstream (far less than the compliant 35%). The 35% flow release downstream should be implemented when the river flow drops to a threshold level of 1.48 m³/s (**Table 6.3**).

New Forest Abstraction Weir

The Sabie River Catchment Operating Rules stipulates that 50% of the flow should be allowed to flow past the abstraction points down the river when the flow drops to a threshold level of 0.566 m³/s (**Table 6.3**). However, the gate is jammed shut and out of order thus releasing no water back into the river. Water is transferred through pipe from the weir to the canal inlet and there are three sluice gates to return flows into the river but these are currently closed and little water flows back into the river.

Edinburgh Abstraction Weir

According to the Sabie River Operating Rules 65% of the flow is supposed to be allowed to flow past the abstraction point down the river when the river flow drops to the threshold level of 3.28m³/s and the capacity of the Edinburgh canal is 1.15m³/s at this flow (**Table 6.3**). This canal feeds into Edinburgh dam, which serves as a storage reservoir and is the main source of domestic water. The canal system is supposed to allow 78% for domestic use and the remaining 22% for irrigation of the Allandale (63.4ha) and Dumfries (25ha) agricultural schemes. However, the irrigation schemes are no longer functioning. Currently all the water is diverted into the canal and no water is released back into the river. Since this canal also serves domestic abstractions it is important that these are not detrimentally affected by the implementation of the proportional flow release requirement at the weir. **Table 6.3** indicates the capacity of canals and these canals are supposed to be operated on proportional allocation system but in practice irrigators have been diverting the entire low flow of the river at the various diversion points. The flow release rules only come into effect when the river flow drops to the level indicated under "**River Flow**"

and the capacity of these canals is based on the percentage of off-take at this flow threshold (**Table 6.3**). However at most of these points little or no water is returned downstream.

Table 6.3 The flow release rules

Canal	Capacity (m ³ /s)	% Releases	River Flow (m ³ /s)
Champagne	0.127	35%	0.195
Dingleydale	0.962	35%	1.480
New Forest	0.283	50%	0.566
Edinburgh	1.150	65%	3.280

Source: DWAF, 2003.

6.2 WATER DISTRIBUTION INFRASTRUCTURE

6.2.1 Bulk Water Supply scheme

The water supply scheme area for Inyaka covers nearly 78% (by population) of the communities in the Bushbuckridge Local Municipality (BBRLM) (DWAF 2009b). This also includes the current supply area of Hoxane Water Supply Scheme. There are four sub-schemes areas, which exist in Bushbuckridge of which three are supplied from Inyaka Regional Water Works and the other scheme is supplied by Hoxane Treatment works. Hoxane Treatment works also serve Nsikazi North.

Currently the Inyaka Regional Water Supply Scheme is developed as the main source of water supplies to the area spanning from Bushbuckridge near Inyaka Dam to Acornhoek and Timbavati in the North (from Dwarsloop / Thulamahashe to Welverdiend in the North West from Marite to Alexandria / Soweto in the South and Zoeknoeg and Wales in the West. The raw water for the treatment plant is obtained from the Inyaka Dam located on the Marite River a major tributary of the Sabie River system. Three schematic layouts of the above regional water supply schemes are provided in **Figure 6.5** to **Figure 6.7**.

A complete list of water treatment works currently in operation in the Sabie-Sand catchment is shown in **Table 6.4** and they are managed by either Bushbuckridge Water Board or by Bushbuckridge Local Municipality. Only Hazyview plant is managed by Mbombela Local Municipality. The underutilisation of the treatment works is because the bulk water supply infrastructure to the northern and north western water supply areas has not yet been completed. These supply areas are largely dependent on the local water treatment works. The majority of the treatment works are not licensed.

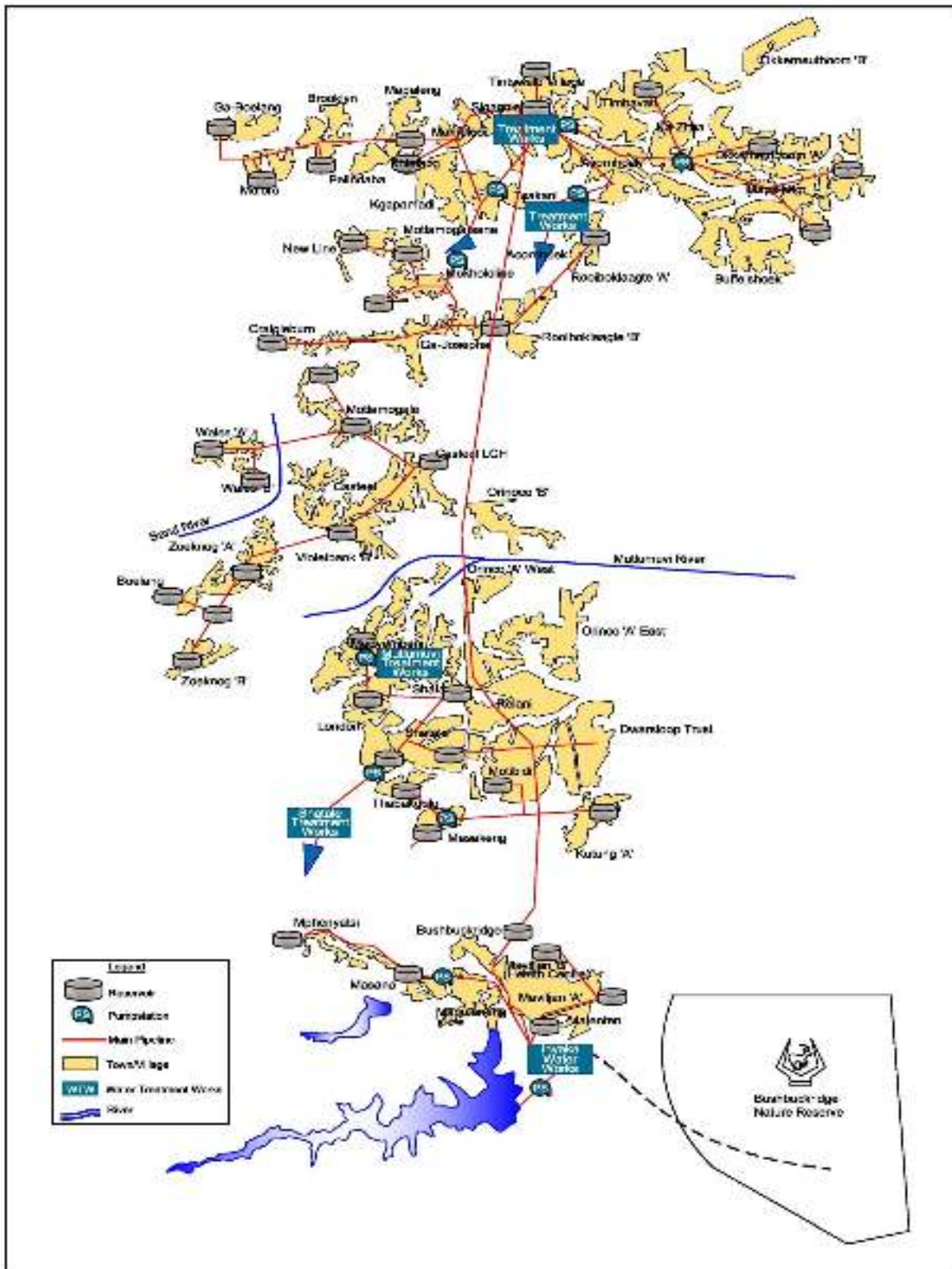


Figure 6.5 Schematic layout of the Bushbuckridge to Acornhoek bulk water supply scheme (DWAF 2009b)

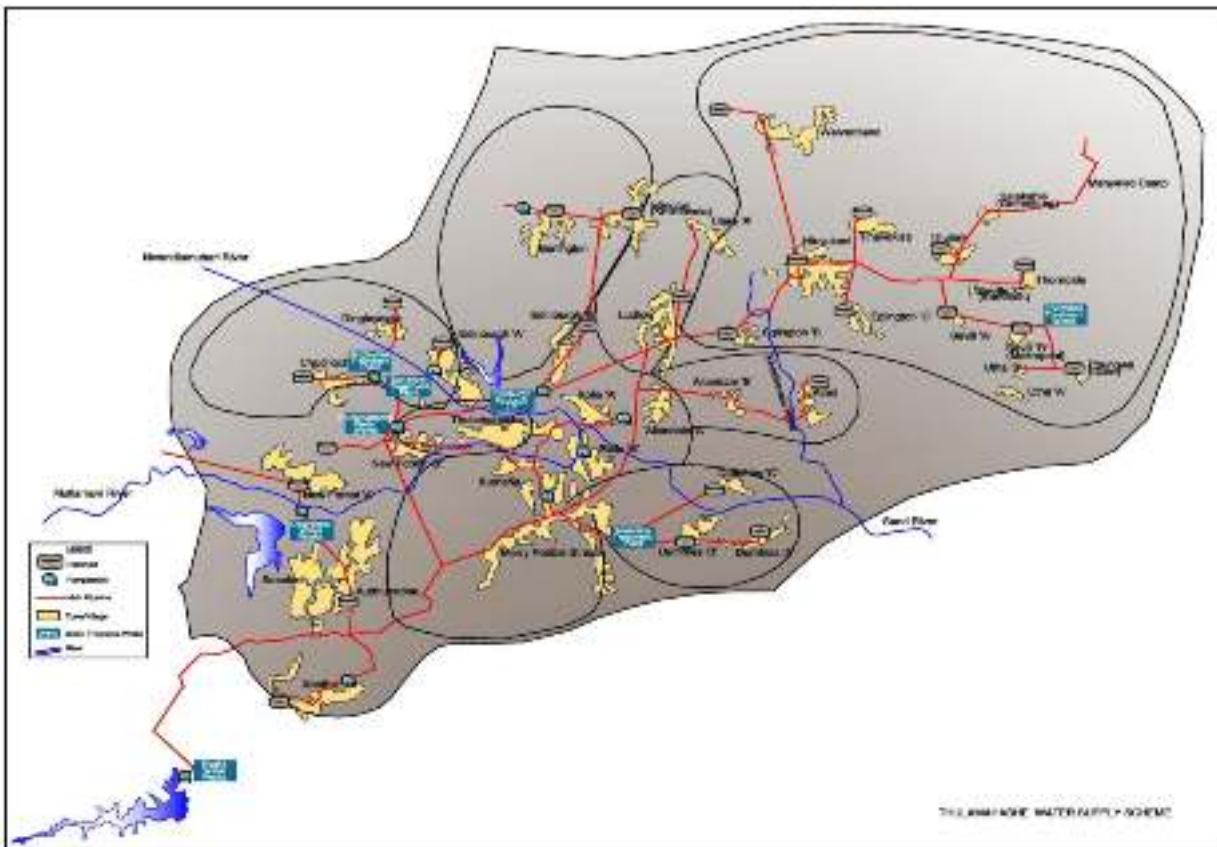


Figure 6.6 Schematic layout of Dwarsloop/Thulamahashe bulk water supply scheme (DWAf 2009b)

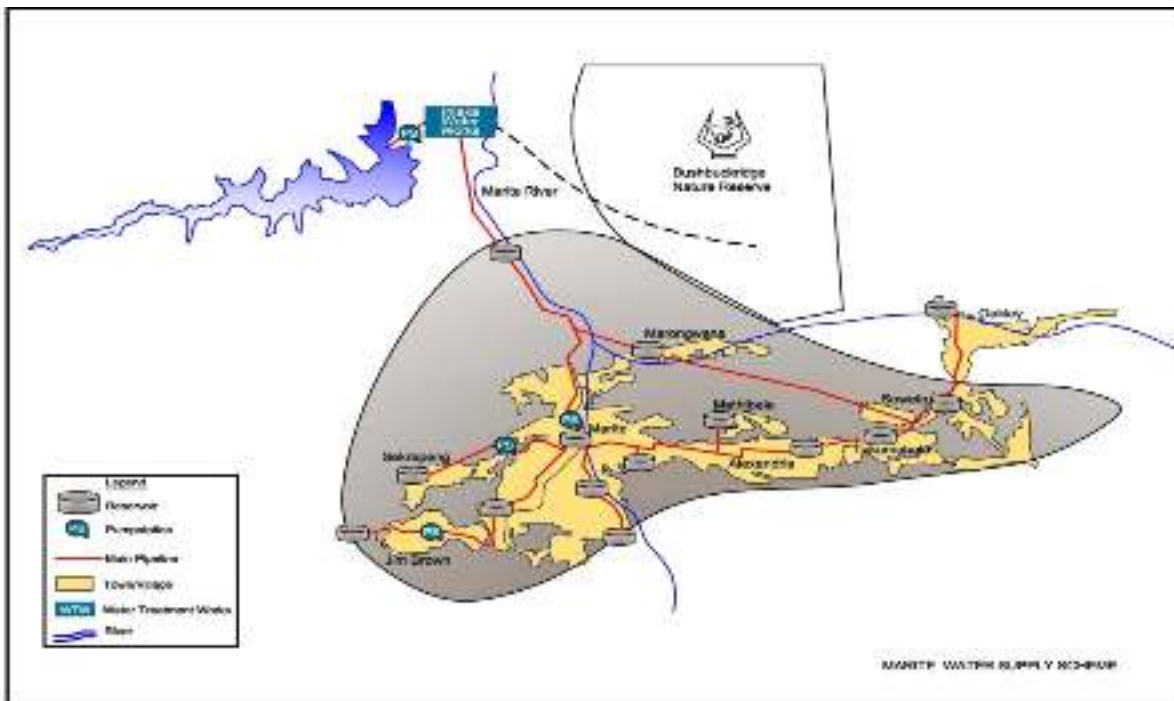


Figure 6.7 Schematic layout of the Marite bulk water supply scheme (DWAf 2009b)

Table 6.4 Water Treatment Works in Sabie-Sand catchment

Water treatment plant	Managed by	Plant capacity (Ml/day)	Lawfulness status (m ³ /annum)
Acornhoek	BRR Water Board	6	Requires licensing
Acornhoek (sigagule)	BRR Local Municipality	No information	Requires licensing
Okkernootboom	BRR Local Municipality	No information	Requires licensing
Dingleydale	BRR Local Municipality	0.1	Requires licensing
Sand river	BRR Water Board	1	Requires licensing
Thulamahashe	BRR Water Board	9	Requires licensing
Zoeknag	BRR Local Municipality	2765	Requires licensing
Shatale	BRR Water Board	1.8	Requires licensing
Dwarsloop	BRR Water Board	4.5	Requires licensing
Edinburgh b	BRR Water Board	1.2	Requires licensing
Edinburgh a	BRR Water Board	1	Requires licensing
Thorndale	BRR Local Municipality	No information	Requires licensing
Injaka	BRR Water Board	50	White Paper
Marite	BRR Local Municipality	3.6	Requires licensing
Hazyview town	Mbombela Municipality	4.2	Requires licensing
Hoxane	BRR Water Board	26	Requires licensing
Nsikazi north (Nyongane)	BRR Water Board	No information	Requires licensing
Cork	BRR Local Municipality	No information	Requires licensing

6.2.2 Water Transfers

Bosbokrand Transfer Pipeline from Sabie to Sand catchment

The White paper (DWAF, 1995) concluded that the proposed Inyaka Dam was the most economical first-phase development of the water resources of the Sabie catchment. In order to supply the water requirements in the Sand catchment construction of the Bosbokrand Transfer Pipeline was proposed. The current maximum discharge through the pipeline is 13 million m³/annum, but can increase to 13 million m³/annum. The Inyaka White Paper (DWAF, 1995) and the Operating rules (DWAF, 2003) both indicated that there is sufficient water for additional irrigation development in the Sabie and the Sand catchments following completion of Inyaka Dam. The capacity of the Inyaka Water Treatment works is currently being extended to 25 million million m³/annum.

Transfer from Sabie to Crocodile catchment

Transfers from Sabie River are made to domestic users in the Nsikazi North WSS in the lower crocodile catchment. The current transfer volume is estimated to be 8 million m³/annum.

6.2.3 IRRIGATION SCHEMES AND CANALS

Irrigation is a significant factor in the Sabie catchment. The main irrigation schemes are administered by the Sabie Irrigation Board and the White Waters Irrigation Board. The Sabie scheme is supported by the run-of-river transfers to the Sabie canal and the White Waters scheme is supported by releases from Da Gama Dam and run-of-river transfers. Hoxane

Irrigation scheme covering Calcutta, Belfast and Cork villages (**Table 5.8**), abstracts water directly from the Sabie River. This scheme is being revitalised by the Department of Agriculture.

Abstractions for irrigation in the Sand River are mostly run-of-river supported by supplies from small dams such as Edinburgh, Orinoco and Champagne. The main irrigation schemes in the Sand River catchment are Dingleydale, New Forest and Champagne. The schemes are bordered by the Tlulanziteka River on the northern side, the Mutlumuvhi River on the southern side and Thulamashe town on the eastern side. The main characteristics of the irrigation schemes in the Sand River sub-catchment are as shown in **Table 6.5**.

Table 6.5 Irrigation schemes in Sand River sub-catchment

Scheme	Dingleydale	New Forest	Champagne
Area(ha)	1031	622	3341
Cultivated area(ha)	410	250	265
Water source	Tlulanziteka river	Mutlumuvhi river	Klein Sand river
Registered: total volume (m³/annum)	5 079 376	3 584 960	-
Canal capacity (m³/s)	0.962	0.283	0.127

7 ECOLOGICAL RESERVE

In South Africa the ecological Reserve is defined as a function of the natural flow. While this is a useful method to describe the ecological flow requirements, it creates problems with real-time implementation of the Reserve simply because the natural flow in a system is not known at any point in time. In order to estimate the natural flow, and hence the ecological flow requirements, real-time hydrological models are required which need to be provided with accurate daily rainfall recorded over the catchment in question. A short-coming in models which are currently attempting to implement the Reserve in real-time is the lack of real-time rainfall data to drive the hydrological model (Hughes et al., 2008). The South African Weather Services have closed down most of their real-time rainfall stations and while they are developing radar and satellite techniques for recording rainfall, these techniques are not yet accurate enough for use in hydrological models. ICMA has begun installing additional real time rainfall stations and therefore in future the situation should improve. An alternative method, which is not a function of rainfall to derive natural flows, was developed for the Crocodile East Real Time Decision Support System (DWA, 2010). This approach defines the natural flow as simply the observed flow plus the water use within the catchment upstream of the flow gauge from which the observed flow is obtained. This approach has also been developed for the Sabie-Sand River System and its being implemented (See section 8.3 for more details).

The alternative methodology is expressed mathematically as follows:

$$\text{Natural flow}_t = \text{Observed flow}_t + \sum \text{Water use}_t \dots\dots\dots \text{Equation 7.1}$$

Where t refers to a time interval rather than a point in time. The time interval will generally be monthly or daily, depending on the sophistication of the catchment management model.

If there are a significant number of dams in a catchment, the change in storage of these dams will also cause the observed flow to deviate from natural. For example, if large unseasonal releases are made from a dam, the observed flow could even be greater than natural, while during the first summer rains floods are stored and hence the observed flow is much less than natural.

Hence, including this in *Equation 7.1*:

$$\text{Natural flow}_t = \text{Observed flow}_t + \sum \text{Water use}_t + \Delta \text{Storage} \dots\dots\dots \text{Equation 7.2}$$

The actual implementation of real-time naturalisation is not as simple as Equation 7.2 might imply. Firstly, accurate observed flow is required and this must be collected diligently. Then estimating water use by the irrigation sector also presents a challenge since this can vary depending on rainfall. While rainfall is not crucial to this real-time naturalisation process (as it is in the case of a hydrology model) it does improve estimates of irrigation requirements, for instance when it rains irrigation requirements drop.

8 INTEGRATION OF DECISION SUPPORT MODELS

The basic approach followed to develop a near real-time operational Decision Support System (DSS) was to apply finer resolution rainfall-runoff model to model river flows and use of river flow management model to best meet the release from the Inyaka Dam and run-of-river supply to the demand, improve operational efficiency, eliminate unnecessary spills and losses, and meet the international and ecological flow requirements. The developed DSS system has also incorporated an annual allocation model into a real time system which will assist in water resource management and operation in a more sustainable and transparent way and ensure that users do not abstract water to which they are not entitled and also ensure sustainable supply within a 5 year planning horizon. The annual allocation model incorporates a curtailment/rationing component where restrictions can be implemented at different dam storage levels. The DSS will be a useful tool in assisting the water managers to ensure flow for the ecological Reserve and Mozambique remains in the river and is not abstracted.

While parts of the DSS framework (**Figure 8.1**) established for the Sabie River system are centred on a software product called MIKE Floodwatch (e.g. data management and publication of annual allocation model outputs), the rainfall-runoff model, the Reserve model and the river flow model do not form part of Mike Floodwatch as their data formats are not compatible it. Mike Floodwatch was developed by the Danish Hydraulic Institute (DHI) and it integrates spatial data, real-time data, forecast models and dissemination tools in a Geographical Information System (GIS) environment.

DSS Components

The DSS has two main overriding components namely the Medium-Long term operation component and the Short-term operation component as already shown in the DSS framework in Figure 8.1. The framework manages data acquisition and management, system modelling and dissemination of different outputs to stakeholders. The components of the DSS which support both the short and medium-long term operations are:

- Data management system.
- Rainfall-runoff model.
- River flow management (hydraulic) model.
- Water Resources modelling Platform (reserve model, water use rationing and allocation model).
- Information dissemination

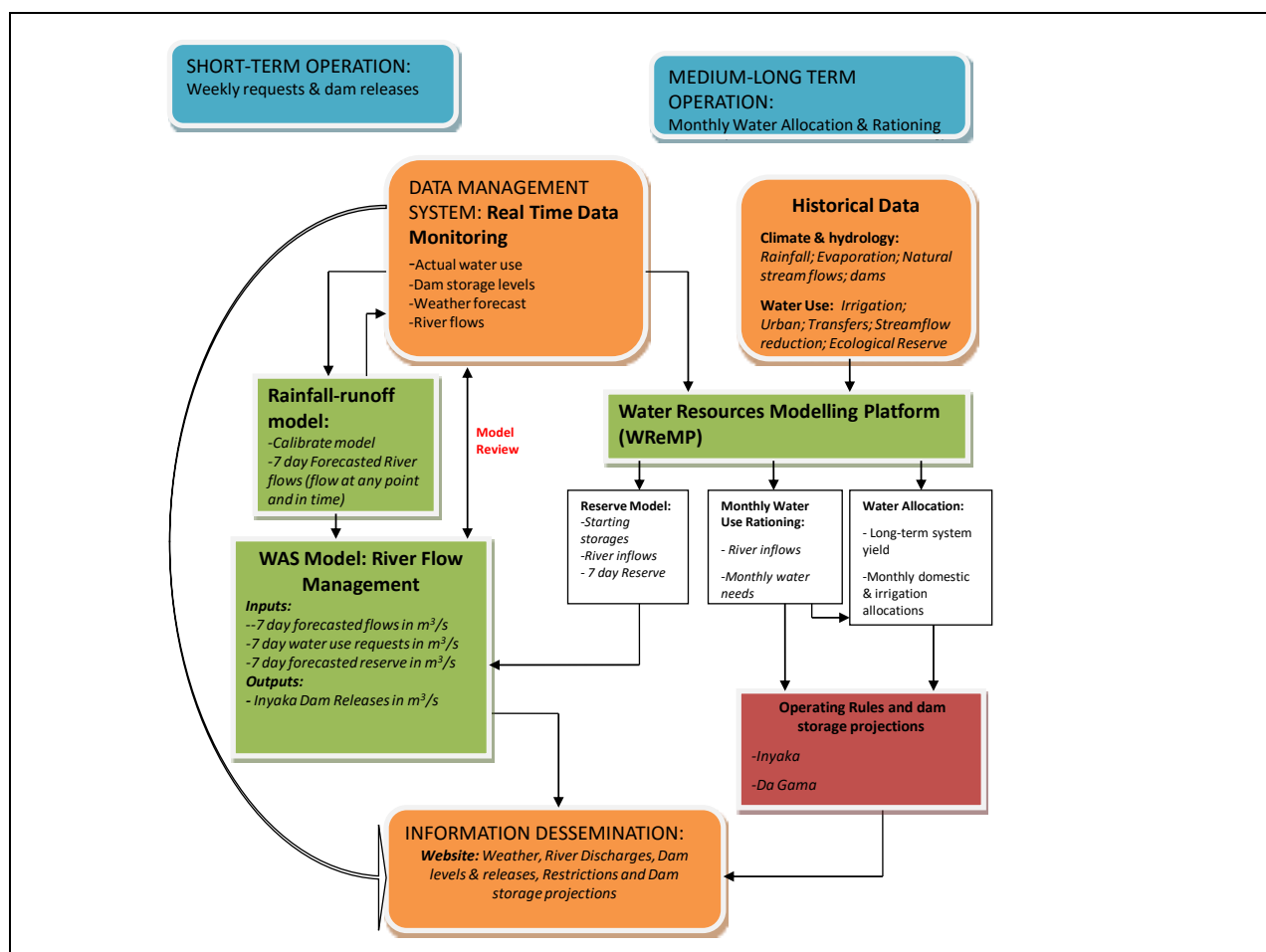


Figure 8.1 Framework for DSS for the Sabie-Sand River System

Data management system

This involves data acquisition and management including real time data monitoring. The information is grouped into data for general view by stakeholders, inputs into rainfall runoff-model, Reserve model, hydraulic model and systems modelling. The following information is stored in the data management system.

- *Recorded data:* status of reservoir levels and river flows are available on real time basis from DWA. This data is available for dissemination to a wider audience (via internet publications and e-mail).
- *Rainfall data:* recently observed and forecasted rainfall is required for general river flow management model, and to drive hydrological and reserve models. This data is sourced from South African Weather Service (SAWS) and the Inkomati Management Agency (ICMA). Weekly rainfall forecasts are available from <http://www.yr.no/> at several points in the catchment and alternative forecasts will be obtained from SAWS.
- *Water requirements:* the current and future water requirements were estimated in 2010 for the Sabie and Sand system.
- *Actual water use:* the domestic water use information is provided by Bushbuckridge and Mbombela Local Municipalities as well as Bushbuckridge Water Board, while irrigation water use information is provided by the Department of Agriculture. This is entered on monthly basis and is disaggregated into weekly requests in the river flow management model.

Monitoring network

The modelling methodologies and particularly the short-term model require near real time data including river flow, observed rainfall, forecasted rainfall, and water use information. The accuracy of the models and hence the quality of information provided to decision makers is highly dependent on the quality of data provided to the system. The enforcement of the operating rules on the system is another very important aspect of requiring actual water use information. Thus a good real time monitoring network is crucial to a successful operation of the system to lead to an efficient water resource management of the Sabie-Sand River System. Along the Sabie River the majority of users (domestic and irrigators) are metered and pump capacities and pumping hours are used to quantify abstractions. This information is provided on weekly basis through an SMS system which forms part of the DSS. The project uses local community members to send SMSs on river levels and water use on weekly basis to DSS currently installed at Inkomati Management Agency (ICMA). More details on monitoring requirements are in Section □.

Sections 8.1 to 8.4 present in chronological order on how the decision support models are linked and will be run. Section 8.1 presents the monthly decision model while sections 8.2 to 8.4 present weekly decision models.

8.1 ANNUAL WATER ALLOCATION AND CURTAILMENT MODEL

The annual water allocation and curtailment model enables managers to make decisions on a monthly basis.

8.1.1 Setting up water resources model

The Water Resources Modelling Platform (WReMP) (Mallory *et al.*, 2011) has been set up for the Sabie River sub-catchment at quinary catchment scale. Restrictions were applied on a trial and error basis to the various user sectors in the catchment until a solution was found, i.e. the maximum possible supply without the dam failing. Through trial and error, the water levels in the Inyaka and Da Gama Dams at which restrictions need to be imposed on the various user groups were determined (**Figure 8.2**). The assurance of supply to irrigators is assumed to be 80% (with 40% restriction, when applied) and 98% for domestic use (with 20% restriction, when applied). These are subject to change by system operating forum which will meet on monthly basis.

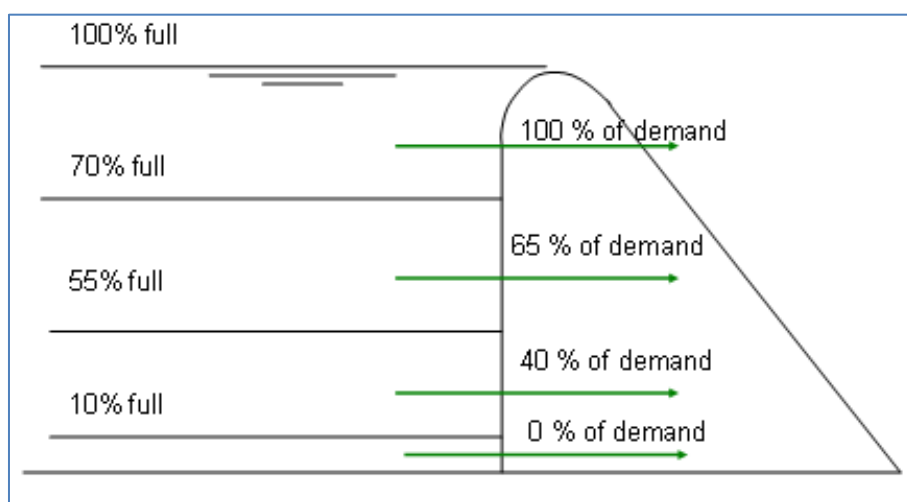


Figure 8.2 Restriction rules at different storage levels

8.1.2 Medium term operation (Water use rationing model)

Medium-term operation within the context of the Annual Operation Model is dealt with by carrying out an analysis every month. This analysis entails regenerating the stochastic flow sequences using the flow into the Inyaka Dam as an indicator of the antecedent conditions in the catchment. A simulation is then carried to determine a range of possible trajectories for the Inyaka Dam. Superimposed on these trajectories are the recommended levels at which restrictions must be imposed on the various user sectors (domestic and irrigation) making use of water out of Inyaka Dam. Hence every month a decision can be made on whether or not to impose restrictions on users based on the actual level of the dam. A similar analysis was carried out to determine operating rules for Da Gama dam. The probability of restrictions can also be derived from the probabilistic trajectories. **Figure 8.3** shows an illustration of the irrigation operating rule and the restriction in the Sabie River System. The graph provide information on the probability that a specific user will have his restrictions imposed to ensure long-term sustainability of the system, which is checked by running the annual allocation model (Section 8.1.3)

The following steps should be followed to run the WReMP model every 1st day of every month:

- i. Update Inyaka Water Balance, obtain monthly data from Amos Msimango who operates Inyaka dam (MsimangoA@dwa.gov.za).
- ii. Update the StochParam.dat file input file in directory C:\Floodwatch\projects\WREMP\Data\SabieSand\Input\Jan2013\StochParam.dat for the three inflows:
- iii. 1.16 EmmetTot.inc
- iv. 0.97 InyakaTot.inc
- v. 0.39 SandTot.inc.
- vi. Open WReMP and enter current MONTH .
- vii. Run historic model and enter starting storages and Run the 101 stochastic runs, and continue running if you already entered starting storages, else re-enter them.
- viii. Import file into excel C:\Floodwatch\projects\WREMP\Data\SabieSand\StOutput\INYAKADAM.ProbPlot.out .

- ix. Paste values into Time Months column and Transpose the values into Time Months rows to generate the reservoir probability trajectories graph as shown in **Figure 8.3**. Export the graph to pdf.

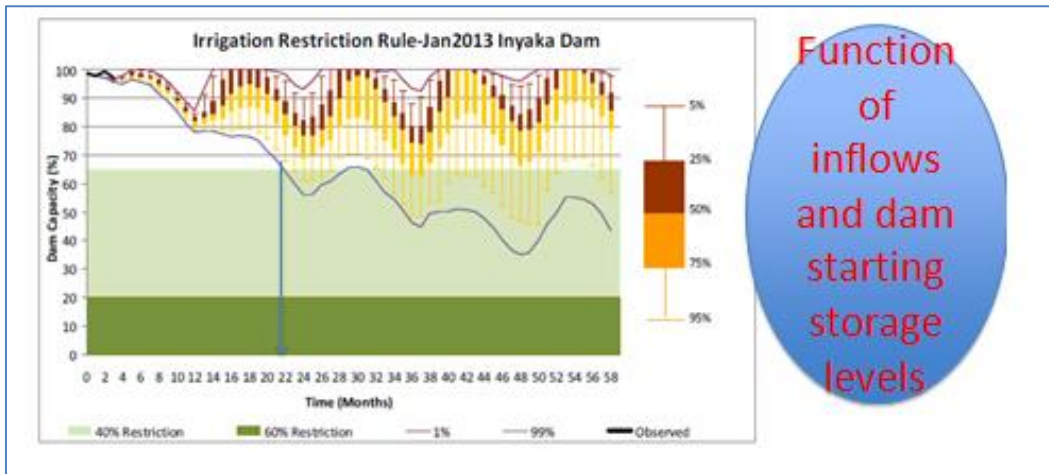


Figure 8.3 Monthly reservoir probability trajectories

8.1.3 Long-term operation (Water Allocation model)

While the WReMP model is used to develop annual operating rules and monthly restriction rules, a check is carried out every time the model is run on monthly basis to ensure that the proposed annual allocations are in line with the long-term yield of the system. The annual yields of Inyaka and Da Gama dams are 50 million m³/annum and 12 m³/annum respectively. According to White Paper (WP D-94) (DWAF, 1995) the yield of Inyaka was estimated to 57.8 million m³/annum. The increased yield in the system would have addressed the projected water shortages in both Sabie and Sand River catchments with the BTP allowing transfer of 25.1 million m³/annum from Inyaka Dam into the Sand River. The discrepancy in yield of Inyaka Dam is due to differences in hydrological estimates during the planning phase of the dam and the recently improved Inkomati Water Availability Assessment Study (IWAAS) in the Inkomati Management Area (DWAF, 2009). In practice the problem arising from the differences in yield and therefore a perception of an under-allocation or an over-allocation of water will be resolved by making the assurance of supply higher or lower respectively.

The next sections 8.2 to 8.4 present **short-term operation models** that assist water managers to make decisions on weekly basis.

8.2 RAINFALL-RUNOFF MODEL

Disaggregation software developed through WRC project (WRC K5/1979) (Mallory and Sawunyama, 2012) to disaggregate Pitman monthly hydrology to a new daily time series using sequencing from ACRU daily hydrology was extended to develop a black-box daily rainfall-runoff model to generate forecasted flows in the Sabie and Sand river systems. The model has very few parameters that are calibrated to be consistent with ACRU natural daily flows (**Figure 8.4**). The reason for developing this model was to enable simulation of forecasted flows which are used as inputs into the River flow management model. The previous study (DWAF, 2003) used ratios of

flows from indicator sites flows to generate tributary inflows at various nodes within the catchment and could not be used forecast future flows.

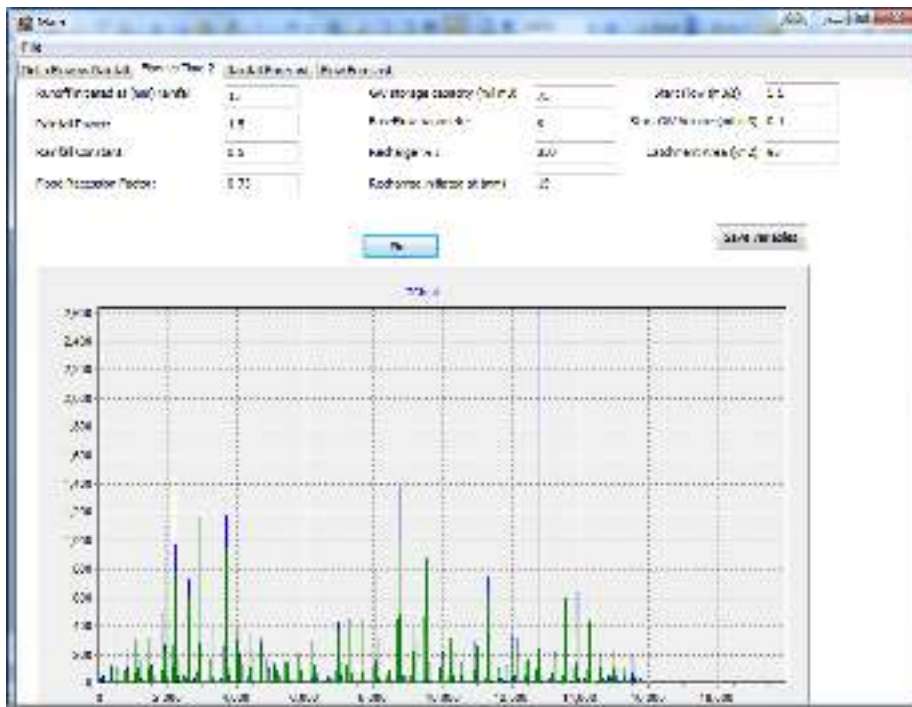
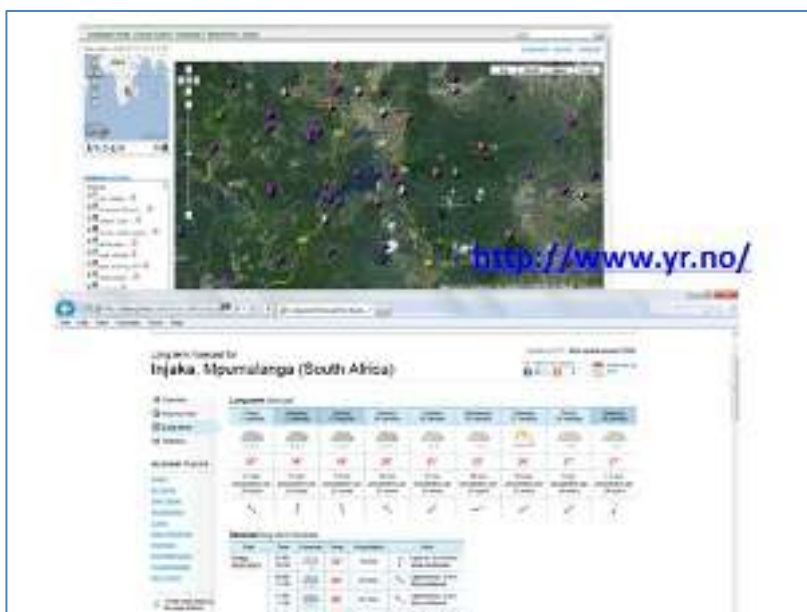


Figure 8.4 Calibration parameters of daily rainfall-runoff model

The following steps are followed to update the flows in the river using the rainfall-runoff model:

- i. Acquire forecast rainfall from www.yr.no/ website (see extract below) for each point in the catchment (Copy and paste in Excel). Satellite data is validated ICMA rain gauge stations (**Figure 8.5**).



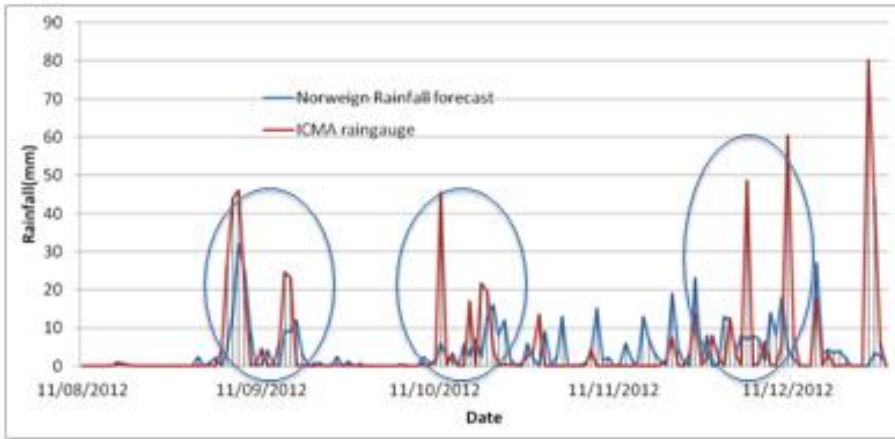
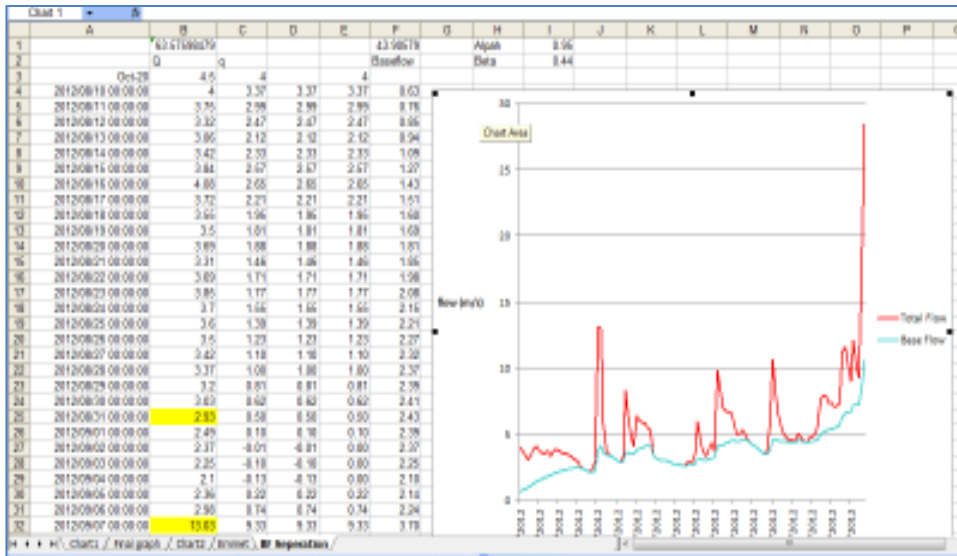


Figure 8.5 Illustration of validation of forecast rainfall with rain gauge data at Emmet Gauging Station

- ii. Download daily observed flows (daily average flows from DWA website:<http://www.dwaf.gov.za/Hydrology/>) for Emmet Gauging Station and Kruger Gate flow gauges.
- iii. Calculate base flows using the Observed vs Forecasted spreadsheet in directory: C:\Floodwatch\projects\RainfallRunoff\Spreadsheet\ Observed vs forecasted_Emmet_ (see extract of spreadsheet below).



- iv. Manually enter observed flows for the current date, baseflows and a weekly rainfall into an input file 'RainFC.prn' in the directory C:\Floodwatch\projects\RainfallRunoff\Data\Daily\RainFC.prn (Use Excel and Text editor –to copy and paste instead of manually entering) (**Figure 8.6**).

	Flow (m3/s)	Rainfall							
	Total	Baseflow	Saturday	Sunday	Monday	Tues	Wed	Thurs	Fri
Emmet	3.74	3.16	2.3	0	0.5	0	1.0	0	1.9
USKrugr	1.55	0.55	2.3	0	0.5	0	1.0	0	1.9
USTraywa	0.53	0.53	2.3	0	0.5	0	1.0	0	1.9
USKrugr	0.71	0.71	1	0	1.1	0.7	0	0	0.7
LowerKrugr	0.27	0.27	1	0	0.4	0.8	0.7	0	1.9
USDeGene	1.92	1.92	1	0	0.4	0.8	0.7	0	1.9
USKrugr	0.00	0.00	1	0	0.2	2.8	0.7	0	1.9
USHogant	0.00	0.00	1	0	0.4	0.8	0.7	0	1.9
USKrugr	0.00	0.00	1	0	0.2	2.8	0.7	0	1.9
USKrugr	0.00	0.00	0.9	0	0.1	1.7	0.7	0	1.9
Champaign	0.11	0.11	2.5	0	0.3	4.4	1.4	0	1.9
USChampaign	0.00	0.00	2.5	0	0.3	4.4	1.4	0	1.9
Dingley	0.20	0.20	2.5	0	0.3	4.4	1.4	0	1.9
USDingley	0.00	0.00	0.9	0	0.1	2.8	0.8	0	1.9
NewForest	0.18	0.18	2.5	0	0.3	4.4	1.4	0	1.9
USNewForest	0.00	0.00	0.9	0	0.1	2.8	0.8	0	1.9
BTP	0.14	0.14	2.5	0	0.3	4.4	1.4	0	1.9
USBTP	0.00	0.00	0.9	0	0.1	2.8	0.8	0	1.9
USKrugr	0.00	0.00	0.9	0	0.1	2.8	0.8	0	1.9
USSabieSand	0.00	0.00	2.5	0	0.3	4.4	1.4	0	1.9
Emmet	0.00	0.00	0.7	0	0.1	2.2	1.5	0	0.7

Figure 8.6 Forecast rainfall input file

- v. Enter the current date and populate RainFC file under Rainfall forecast (Figure 8.7).
- vi. Calculate forecasted flow and is save in the directory C:\Floodwatch\projects\WREMP\Data\SabieSand\FutureFlow.csv. The tributary inflows are negative values which represents inflows into Water Administration Model (WAS) which is presented in Section 8.4.

Sub Catchment	Station ID	Date	Coverage	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Emmet	EMMET	03/12/2012	3.7	3.1	3.68	3.34	3.00	3.40	3.43	3.65
USKrugr	USKRUGR	03/12/2012	1.5	0.5	0.52	0.51	0.51	0.50	0.50	0.50
USTraywa	USTRAYWA	03/12/2012	0.5	0.5	0.52	0.52	0.52	0.52	0.52	0.52
LowerKrugr	LOWERKRUGR	03/12/2012	0.3	0.3	0.32	0.32	0.32	0.32	0.32	0.32
USDeGene	USDEGENE	03/12/2012	1.9	1.9	1.93	1.93	1.93	1.93	1.93	1.93
Hogant	HOGANT	03/12/2012	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
NewForest	NEWFOR	03/12/2012	0.2	0.2	0.20	0.20	0.20	0.20	0.20	0.20
BTP	BTP	03/12/2012	0.1	0.1	0.10	0.10	0.10	0.10	0.10	0.10
Champaign	CHAMP	03/12/2012	0.1	0.1	0.11	0.11	0.11	0.11	0.11	0.11
USChampaign	USCHAMP	03/12/2012	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Dingley	DINGLEY	03/12/2012	0.2	0.2	0.20	0.20	0.20	0.20	0.20	0.20
USDingley	USDINGLEY	03/12/2012	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
NewForest	NEWFOR	03/12/2012	0.2	0.2	0.20	0.20	0.20	0.20	0.20	0.20
USNewForest	USNEWFOR	03/12/2012	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
BTP	BTP	03/12/2012	0.1	0.1	0.14	0.14	0.14	0.14	0.14	0.14
USBTP	USBTP	03/12/2012	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00

Figure 8.7 Forecast flows output screen

- vii. The forecasted flows are compared with historical flows measured at Emmet Gauging Station and Kruger Gate (illustration in for Emmet Gauging Station station is in Figure 8.8).
- viii. Publish the simulated forecast flows stored in directory: C:\Floodwatch\Projects\SabieSand\Publications\sabie_site\WAS_ Outputs\Observed vs forecasted@Emmet.

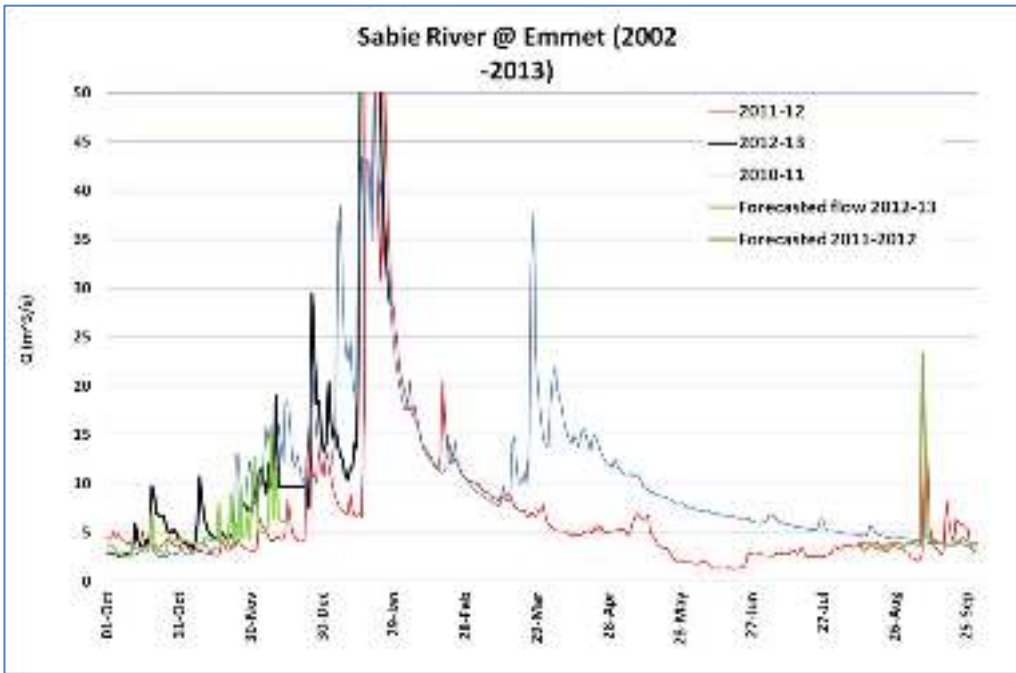


Figure 8.8 Comparison of monthly forecasted flows with historical flows

8.3 REAL TIME RESERVE MODEL

After running the rainfall-runoff model and estimate tributary inflows, the next step is to estimate the Reserve at EWR 3 site, just upstream of Kruger Gate. This is done by running the WReMP model. The following steps are followed in estimating the weekly reserve:

- i. Obtain starting storages for Inyaka and Da Gama Dam

Date of run	Starting storages (million m ³)	
	Inyaka	Da Gama
27/11/2012	123.62	13.18
03/12/2012	124.15	13.42

The starting storage dam levels are provides by Van der Merwe Elna (vanderMerweE@dwa.gov.za).

- ii. Open Sabie Project in WReMP and enter current month.
- iii. Run the historical model in WReMP and update starting storages for the week.
- iv. From WReMP Home page, go to Utilities to run **Estimate natural flow** and an input screen for Reserve model will appear (**Figure 8.9**).

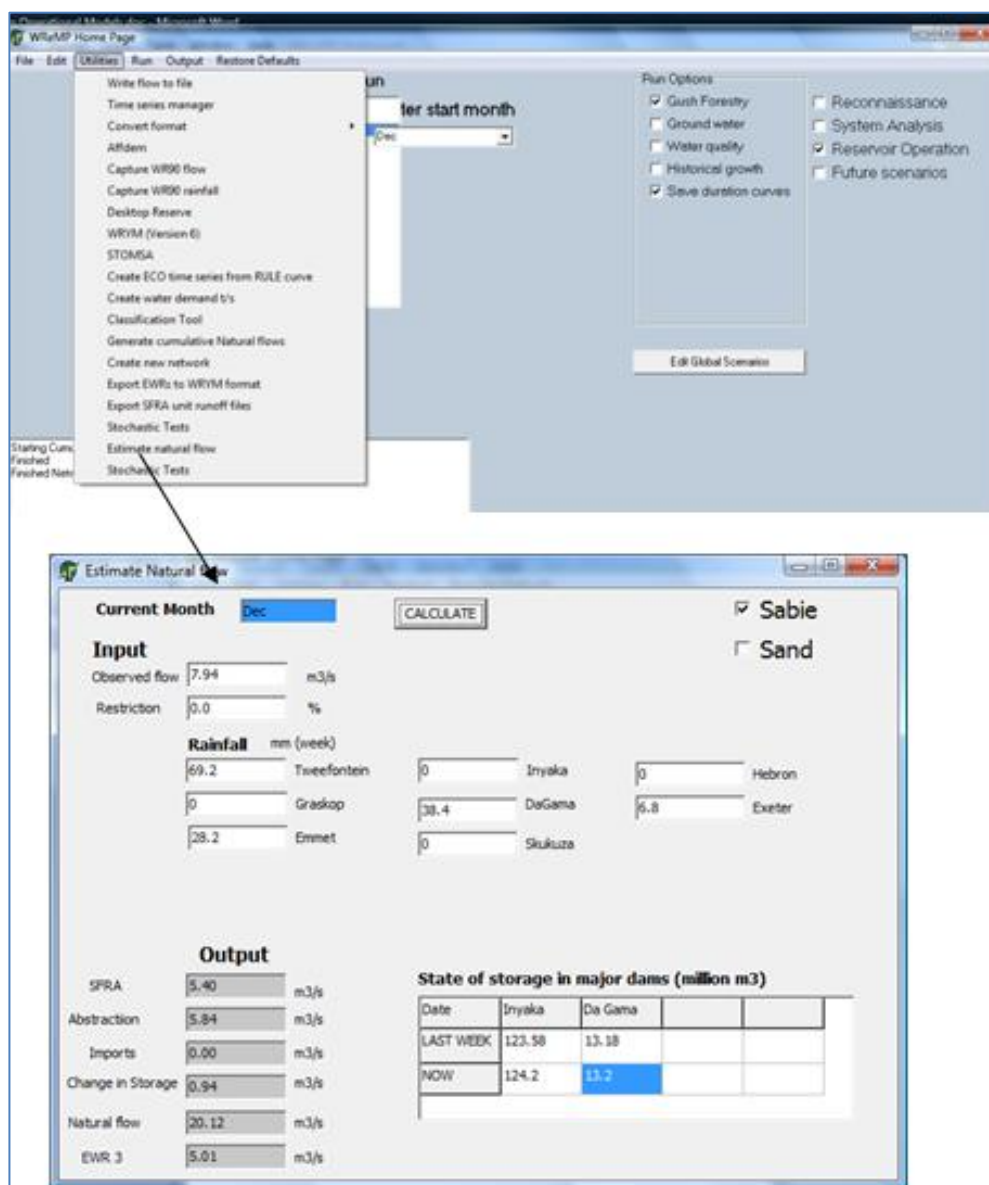


Figure 8.9 Reserve model input file

- v. Insert weekly rainfall input for 8 stations (when it rains, farmers will not irrigate, and this will reduce the abstraction and hence Reserve requirement) available from ICMA website.
- vi. Enter last week state of storage of dams.
- vii. Insert 7 day average observed flow at Kruger Gate (Figure 8.10).

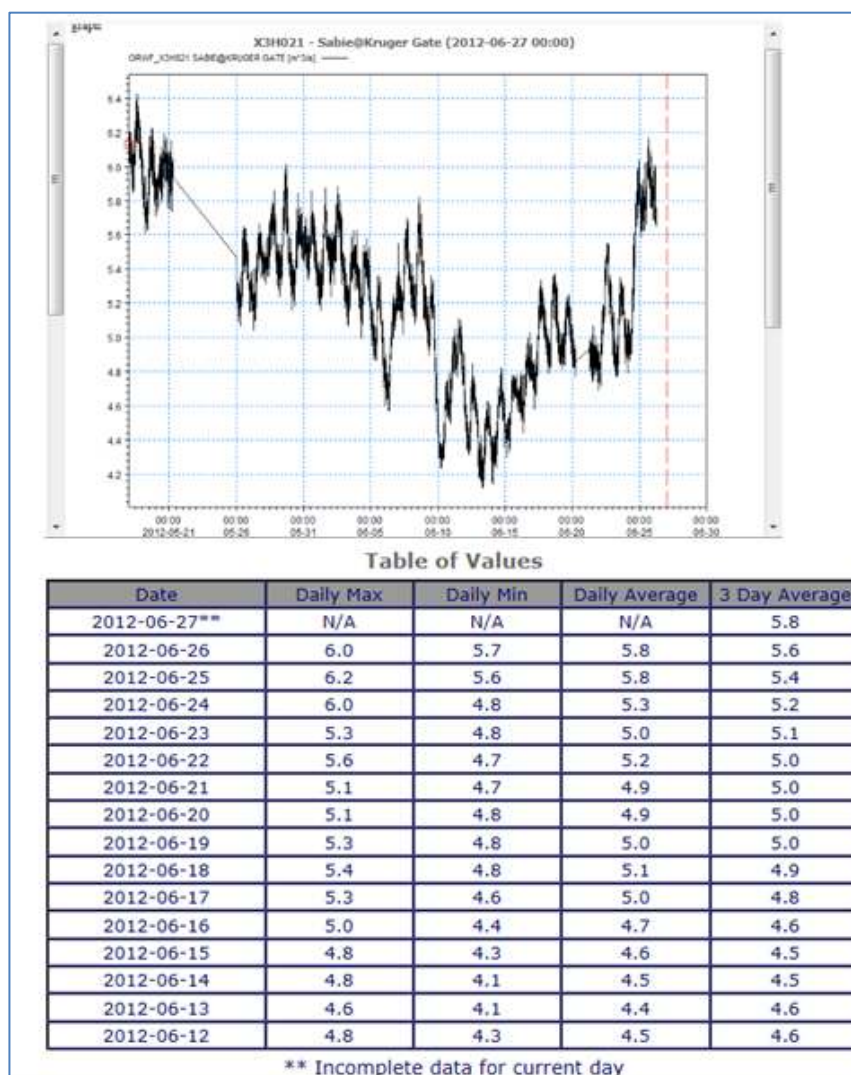


Figure 8.10 Illustration of observed flows at Kruger Gate

- viii. Run the model and the Reserve output (EWR3) is saved into directory C:\Floodwatch\projects\WREMP\Data\SabieSand\FutureFlow.csv (Make sure the month of Rainfall-runoff model is the same the current month the Reserve model is run).
- ix. Update the Reserve spreadsheet and export compliance graph as PDF for publication (**Figure 8.11**) into directory: C:\Floodwatch\Projects\SabieSand\Publications\sabie_site\WAS_Outputs\1 Reserve Kruger Gate.

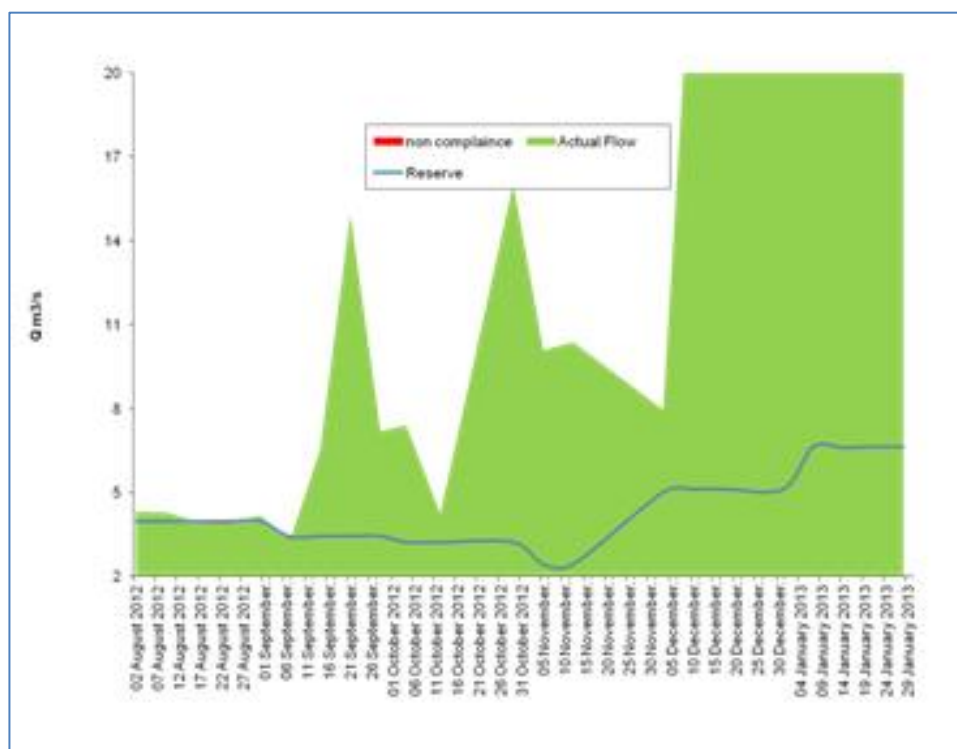


Figure 8.11 Weekly Reserve output graph

8.4 RIVER FLOW MANAGEMENT (WATER ADMINISTRATION SYSTEM (WAS))

Short-term operation of DSS process takes downstream consumptive water use, tributary inflows, international water requirements and environmental water requirements into consideration. The modelling approach and model that was adopted is the Water Administration System (WAS). This model was originally developed for the operational management of canal irrigation schemes (Benadé *et al.*, 1997). The Water Administration System was further developed by NB Systems as a management tool for irrigation schemes to manage water accounts and to plan water supplies to consumers through canal networks, pipelines and rivers. It was further developed to operate as a river management tool (DWAF, 2003) and new algorithms were added to enhance its applicability as part of the current study.

A big advantage of the WAS model is its ease of use and the fact that the degree of operator input is low, while still producing high-confidence predictions of release requirements. The model has ability to perform its operations quickly and with a user friendly output. The previous version of WAS model did not perform "true" hydraulic routing of releases through a system. A simplified mass balance approach was followed, whereby volumes of water ("batches") are moved through the system by time-lagging according to pre-calibrated travel times (or lags), and reducing (or increasing) batch volumes by calibrated seepage rates (based on a lagged accumulation of system demands). Travel times were calculated for steady state conditions, and were based on average velocities calculated with the Manning equation. System losses and gains that are taken into account include evaporation from the open water surface, evapotranspiration from riverine vegetation, seepage from the river channel, tributary and diffuse inflows, and return seepage from irrigation. Evaporation and evapotranspiration are calculated from reach specific weather data and tributary and diffuse inflows are estimated using rainfall-runoff model. The model is real-time enabled, and allows for the import of real time data from a data acquisition system. To calibrate

the model, data from measuring stations are needed to compare the calculated values with the measured flows. However, a new release module was developed as part of the current study to improve its operation and the main differences and advantages of new module are:

- The lag time routine has been improved and the displacement of the hydrographs can now be done in seconds compared to the 5 minute intervals of previous version (more realistic).
- The lag time calibration has been simplified by using velocity look-up tables which can be linked to individual reaches. A default lookup table will be used in cases where a lookup table is not specified. This approach is more user friendly and flexible compared to the previous approach where the velocity was calculated using Manning's equation. The solution of the new approach is more stable compared to previous version.

The main features of the model are:

- The release pattern is designed to ensure that the release matches scheduled abstractions by taking into account the time required for water to flow from the release to abstraction point (i.e. the hydraulic characteristics of the river channel), the present and future natural flow in the river, and flow inputs (diffuse and tributary inflows and seepage returns) and abstractions (irrigators, domestic and industrial users and river and riparian water losses) en route.
- The water requirements for the ecological Reserve are expressed at any number of points in the system. The ecological Reserve requirements are non-consumptive and therefore represent minimum flows that must be maintained at the Ecological requirement sites. The model is capable of determining releases that will maintain these minimum flows.
- A large proportion of water requirements downstream of the Inyaka Dam are met from runoff originating in the catchment downstream of the dam. In addition, return flows to the river system, and seepage and evaporation from the river channel and evapotranspiration from the riverine vegetation affect the water balance of the system to varying degrees. Releases from the dam are therefore only required to supply user requirements when these exceed the flow generated downstream of the dam. A detailed manual on the application of the WAS model is available.

The procedure to update the Water Administration model after running the rainfall-runoff model and the Reserve model is as follows:

- i. Start WAS and chose Sabie project, password: 'masterkey'
- ii. Import the Flow input File from directory (C:\Floodwatch\projects\WREMP\Data\SabieSand\FutureFlow.csv) into WAS.
- iii. Update measured flow records for Inyaka Outflow and Kruger Gate from DWA website (<http://www.dwaf.gov.za/Hydrology/>) for the past 7 days in directory (C:\Floodwatch\projects\WREMP\Data\SabieSand\Observed Flow.csv)
- iv. and import into WAS. The import facility is also used to imported water use into WAS at different abstraction points. **Figure 8.12** shows the importing window.

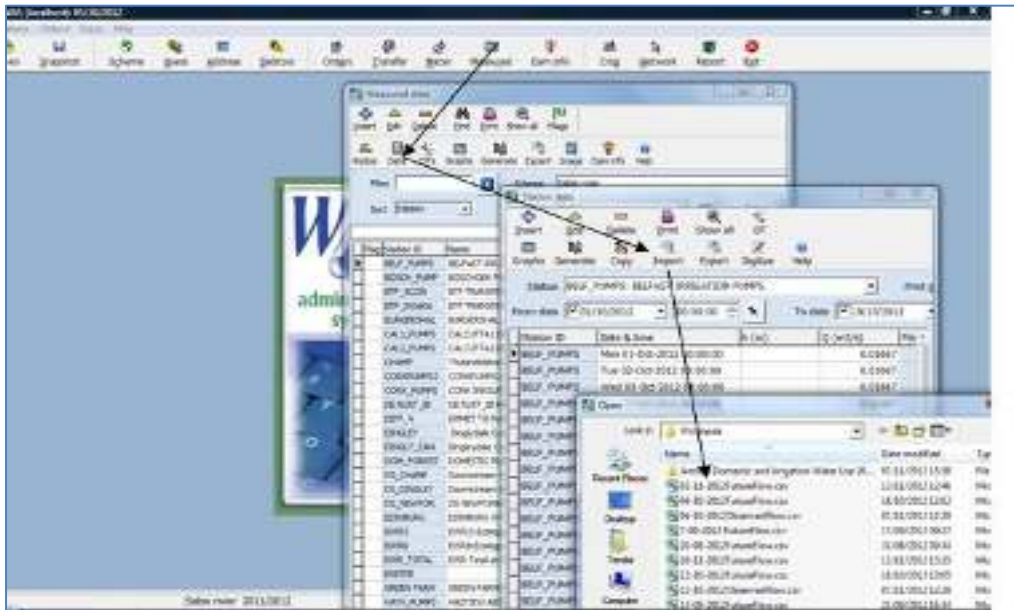


Figure 8.12 Importing flow and water use data into WAS

- v. After adding flow and water use updates, run the Network to calculate dam releases (SBI-Sabie network). First define the week (Figure 8.13) and then run the release model (Figure 8.14).
- vi. After model run, generate graphs (Figure 8.15) and export as PDF files for publication into directory: C:\Floodwatch\Projects\SabieSand\Publications\sabie_site\WAS_Outputs\Nyaka Release.

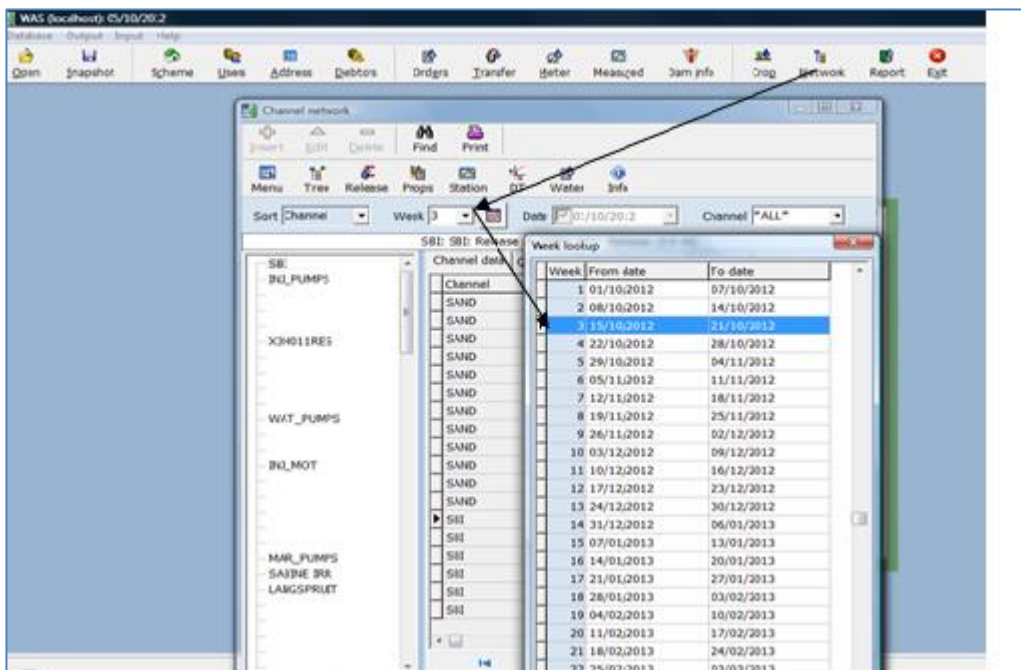


Figure 8.13 Define the week

9 MONITORING FOR REAL TIME MANAGEMENT

The management of the water resources and the river flows is on an active basis in the Sabie River sub-catchment and is on a passive basis in the Sand River sub-catchment as stated earlier. The management objective is to ensure that the river flow and the requirements of the ecological Reserve with the least possible curtailment and that the Inyaka Dam will not be emptied, even under severe drought conditions while maximising the use of the stored water.

Management decisions in the Sabie River sub-catchment are largely based on recent, present and future weather conditions, river flow and reservoir storage and are supported by the annual allocation model, the river flow management model and the ecological Reserve estimation model. The instrumentation is required to provide real time data on river flows and certain key water abstractions within the system and to support the use of the decision support models. This data is required in order to:

- Determine real time ecological Reserve requirements;
- Estimate real time unregulated flows in the system;
- Estimate losses in the system;
- Monitor actual flows against target flows; and
- Calibrate the river flow management model.

It is envisaged the DSS comprises of:

a) Calibrated system

- Generate time series based on historical data;
- Determine model parameters.

The calibrated system is used to estimate parameters using historical data and investigate the performance of hydrological model. These parameters are then used in the forecasting model. The mean areal precipitation and evapotranspiration will be computed from the point values.

b) Operational forecast system

- Generate short-term river and flood forecast using calibrated parameters.

Once a model is calibrated for a basin it is used operationally with real-time hydro-metrological data to forecast river flows and levels.

Figure 9.1 shows the location of real time rainfall and flow gauging stations in the Sabie-Sand River System to for use in the operation of decision support models.



Figure 9.1 Real time rainfall and flow gauges

The Annual allocation model will be used at monthly intervals at most, the river flow management model and ecological Reserve model will be used on weekly basis at most. The data requirements in the Sabie River sub-catchment for these models are as follows:

Annual allocation model

- Volume of water stored in Inyaka and Da Gam dams at the start of the month;
- Inflows into the dams at the start of the month.
- Inflow at the gauging station X3H023 (Emmet Gauging Station) at the start of the month;
- Total volume of water diverted from the Sabie River upstream of the Emmet gauging station by the canal X3H024 at Albany during the month;
- Estimates of future water abstractions from the catchment of the Inyaka Dam, from the dam by the Bosbokrand Transfer Pipeline, from the Marite River and its catchment downstream of the Inyaka Dam, from the Sabie River by the canal at Albany and from the Sabie River downstream of the river flow gauging station at Emmet up to Kruger Gate.

Ecological Reserve Model

- Real time rainfall from ICMA and SAWS stations.
- Weekly starting storages of Inyaka and Da Gama dams and previous week storages.
- Irrigation restriction levels.
- Previous week 7 day average river flows at the gauging station X3H021 (Kruger National Park Skukuza).

River flow management model

- Daily river flow at the river flow gauging station at Emmet;
- Daily flow being diverted from the Sabie River upstream of the Emmet Gauging Station by the canal at Albany;

- Daily flow being released into the Marite River at Inyaka Dam or at the river flow gauging station X3H011 (Injaka);
- Forecast daily rainfall for the next 7 days for key tributary points (<http://www.yr.no/>);
- Forecast average daily river flow at the indicator site at Emmet Gauging Station (observed river flow at the gauging station at Emmet plus the flow being diverted from the Sabie River upstream of the Emmet gauging station by the canal at Albany) for the next 7 days;
- Forecast daily average ecological Reserve requirement at EWR site 3 for the next 7 days;
- Forecast daily average domestic and irrigation water abstractions from the Marite River downstream of the Inyaka Dam and from the Sabie River downstream of the river flow gauging station at Emmet Gauging Station at each of the abstraction points for the next 7 days;
- Daily river flow at the river flow gauging station X3H021 (Kruger National Park Skukuza).

In the case of the Sand River sub-catchment it is only necessary to monitor the following in near real time:

- Daily quantities of water abstracted from the rivers for domestic use;
- Daily transfers of water from the Inyaka Dam by means of the Bosbokrand Transfer Pipeline; and
- Daily river flow at the river flow gauging station X3H008 (Exeter).

Daily water levels measured at Champagne, Dinglydale, and Newforest sites to ensure implementation of operating rules as illustrated in **Figure 9.2**.

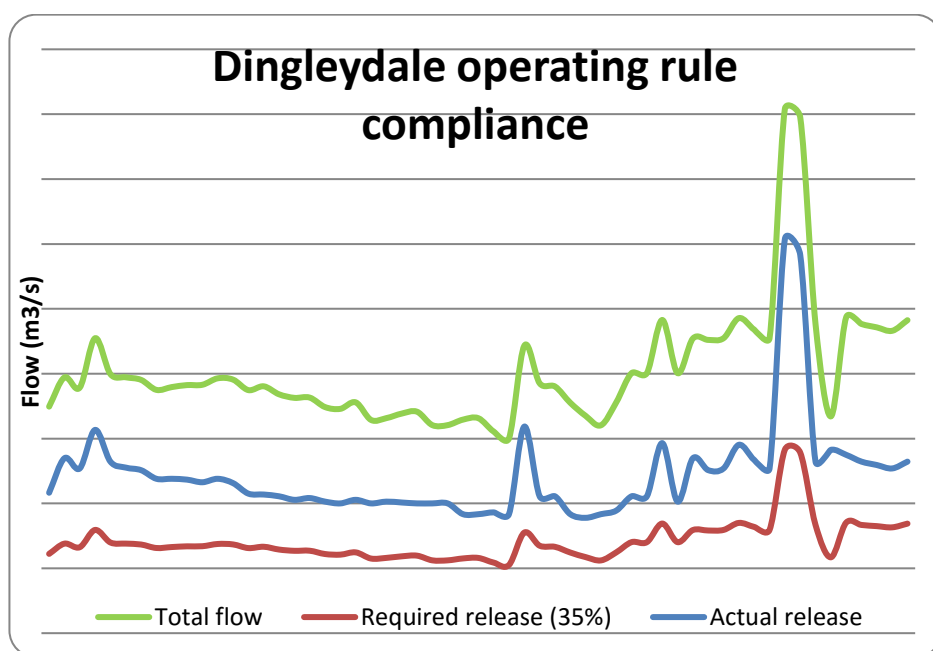


Figure 9.2 Real time implementation of operating rule at Dingleydale weir

The domestic and irrigation water uses in the Sabie River sub-catchment are estimated from records of pump capacities and duration of pumping. The data is provided by the following organisations and the contact persons on monthly basis:

- Bushbuckridge Municipality(Rodgers Baloyi: rodgersbaloyi@yahoo.com)
- Mbombela Municipality (Adelaide Nxumalo:

- Adelaide.Nxumalo@mbombela.gov.za
- Bushbuckridge Water Board (Esther Radingwana: radingwanae@bbrwater.co.za)
- Department of Agriculture (solomonbaloyi@gmail.com)

As part of this project an SMS or phone system was developed to allow data to be sent from field measurements to ICMA database server and the program is operated as follows:

- Install Nokia_PC_Suite_ALL.exe on your PC.
- Connect via Bluetooth or Data cable.
- Receive sms on the: Phone Number:
+27711625729
A typical sms consists of this:
Flow: 1 ID WaterLevel
Pump: 2 ID Hours Volume
Water level is in (m)
Volume is in (m³) (Volume is optional)
- Open Nokia_PC_Suite and go to tools messages



- Copy all messages and export messages and paste in data.csv file in SMS program and then run sms.py program to save data for each station ID.



9.1 REAL TIME RAINFALL STATIONS

ICMA through the operational planning research in the Inkomati WMA inter alia the RISKOMAN and WATPLAN projects installed 5 real time rainfall stations in the Sabie-Sand River catchment (**Figure 9.2**) and a list of names of these stations is presented in **Table 9.1**. Two of these real time operational rainfall stations are managed by South African Weather Service (SAWS).

Table 9.1 List of real time rainfall stations in the Sabie-Sand catchment

Organisation	Name of rainfall station
SAWS	Graskop
SAWS	Skukuza
ICMA	Tweefontein
ICMA	Emmet
ICMA	Da Gama
ICMA	Exeter
ICMA	Hebron

9.2 REAL TIME FLOW GAUGES

ICMA installed six (6) flow data loggers as backup to DWA streamflows in the Sabie-Sand sub-catchment through RISKOMAN and WATPLAN projects. Using the budget from this study it was found essential to add three new flow gauging stations in the Sand River sub-catchment downstream of the three canal abstraction points to allow implementation of flow diversion rules. Site visits to the upper Sand catchment were undertaken in December 2010, July 2011 and December 2011 where suitable hydraulic cross-sections were selected and hydraulic data was collected at each of the three abstraction sites. A discussion of each site and the hydraulic data collected is presented below. The list of real time flow gauges in the Sabie-Sand catchment is presented in **Table 9.2**

Table 9.2 List of real time flow gauges in the Sabie-Sand catchment

Organisation	Name of flow gauge
*DWA/IWR Water Resources	Champagne
*DWA/ IWR Water Resources	Newforest
*DWA/ IWR Water Resources	Dingleydale
ICMA /DWA	Da Gama Outflow (X3H020)
ICMA/DWA	Inyaka Outflow (X3H011)
ICMA/DWA	Emmet (X3H023)
ICMA/DWA	Kruger Gate (X3H021)
ICMA/DWA	Lower Sabie (X3H015)
ICMA/DWA	Exeter (X3H008)

*DWA/IWR Water Resources: these are gauge plates installed during this study to measure water levels only.

9.2.1 Champagne Site

The Champagne diversion structure is situated on the Nwandlamuhari River. The irrigation canal was found to be completely silted up and of no use to the agricultural schemes at present with all water that is diverted at the weir being returned to the river at the return structure. However, there is an indication by the schemes that they intend to de-silt the canal and thus the analysis on the river was still undertaken.

The Nwandlamuhari River consists of bedrock, boulders and fine sediment. The selection of a suitable cross-section for establishing a flow gauge, downstream of the return structure, was difficult. The reasons being, (i) overgrown vegetation limited the line of sights for the survey (ii) bed material was alluvial and thus not stable and therefore not suitable as a gauging site and (iii) multiple channels exist in the bedrock (i.e. stable) sections of the river.

The cross-section selected for flow calibration is illustrated in **Figure 9.13** and it is noted that the site is not ideal for measuring high flows as the left bank consists of vegetation and sediment which could result in the profile changing. However, the high flows are not crucial in this study as the flow release rules (refer to **Table 6.3**Table 6.3) come into effect during the low flow periods.

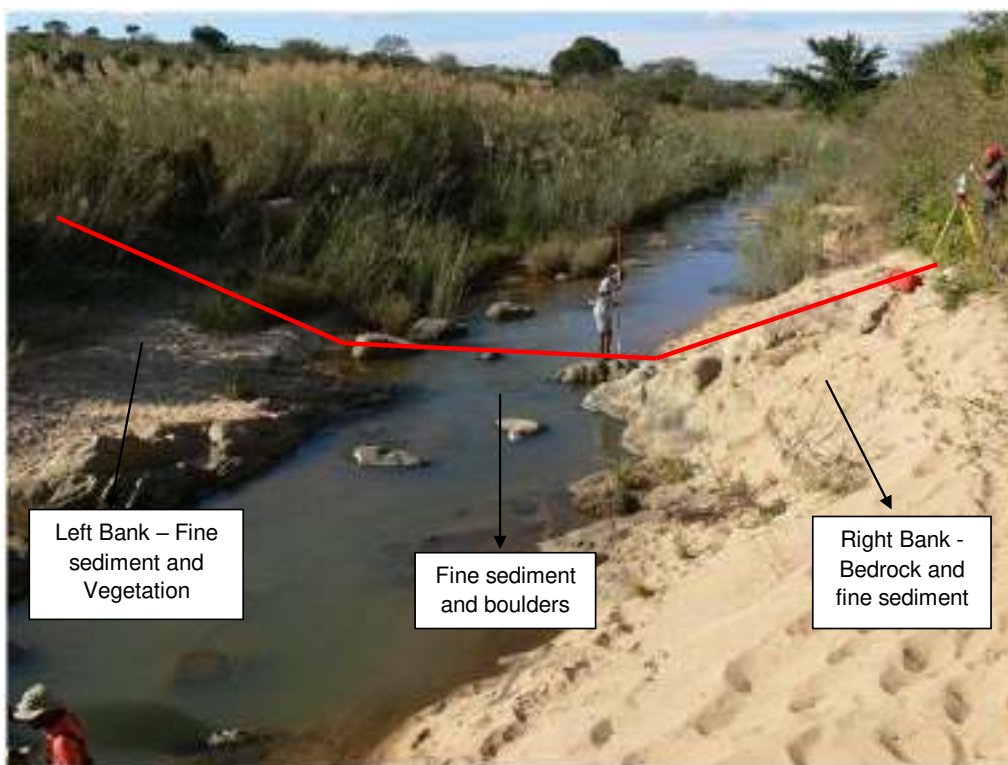


Figure 9.3 Champagne cross-section (red line) selected for rating of streamflow gauge

9.2.2 New Forest Site

The New Forest diversion structure is situated on the Nwarhele River. The irrigation canal is in good condition and is operational (**Figure 9.4**). The canal is parabolic in shape and a profile of the canal was surveyed. The New Forest river cross-section selected is bedrock with fine sediment deposited on the left bank (**Figure 9.5**) as the section is on a slight bend. It is not ideal

to select a cross-section on a bend as the assessment of the hydraulic characteristics is less certain. However, the bedrock at the site was ideal as it provides a stable section to be rated.



Figure 9.4 Flow measurements at New forest irrigation canal



Figure 9.5 New Forest cross-section (black line) selected for rating streamflow gauge

During the July 2011 site visit, it was found that the site selected at New Forest was being used by the local tribes for initiation ceremonies. The ceremonies take place from June to August each year and no 'outside' people are welcome during this period as the harmony of the area will be affected and therefore no data could be collected during the July 2011 visit.

9.2.3 Dingleydale Site

The Dingleydale canal diversion weir is situated on the Mutlumuvi River. The irrigation canal is in good condition and is operational. The canal is parabolic in shape and a profile of the canal was surveyed on 2010 site visit. However, during the December 2010 visit, a suitable cross-section could not be obtained at Dingleydale river as the flow was too high to undertake a survey or flow measurements. During the second site visit, a cross-section (**Figure 9.6**) was identified and a profile and flow measurements were undertaken.



Figure 9.6 Dingleydale cross-section selected for rating streamflow gauge

9.2.4 Hydraulic data collection

Fixed stations were installed at each site using a local datum and the cross sectional profiles surveyed using a total station. The flow rates were measured during each site visit using the velocity area method. The measured discharges and flow depths are provided in **Table 9.3** together with the dates when the data were collected.

Table 9.3 Hydraulic data (rating) collected

Site	Date	Discharge (Q, m ³ /s)	Max. flow depth (y, m)
Champagne	20/12/2010	0.763	0.70
	13/07/2011	0.246	0.61
	14/12/2011	0.216	0.60
New Forest River	21/12/2010	2.520	0.84
	13/12/2011	0.450	0.55
New Forest Canal	21/12/2010	0.247	0.53
	13/12/2011	0.216	0.52
Dingleydale River	13/07/2011	• 0.441	• 1.15
	14/12/2011	0.223	1.08
Dingleydale Canal	13/07/2011	0.248	0.47
	14/12/2011	0.207	0.44

9.2.5 Hydraulic data modelling

The observed rating data (discharge-depth relationship) at each site has been extended using Manning's resistance relationship. The surveyed water surface slopes are given in **Table 9.4** and these have been used in conjunction with estimates of Manning's resistance coefficient (**Table 9.4**) to synthesize rating data for discharges higher or lower than those measured. Continuous rating functions of the form given by *Equation 9.1* have been fitted to the measured and modelled data.

$$Q = ay^b + c \dots \dots \dots \text{Equation 9.1}$$

where y is the flow depth (m), Q is the discharge (m³/s), and a , b and c are regression coefficients, listed in **Table 9.5** and the rating function plots are provided in section 9.1.7.

Table 9.4 Surveyed water surface slopes and manning resistance coefficient estimates

Site	Date	Discharge (Q, m ³ /s)	Water Slopes – surveyed and estimated for modelled	Manning Resistance (n)
Champagne	20/12/2010	0.763	0.003	0.050
	13/07/2011	0.246	0.002	0.150
	14/12/2011	0.216	0.002	0.150
	Modelled	8.000	0.003	0.050
New Forest River	21/12/2010	2.520	0.0005	0.020
	13/12/2011	0.450	0.0002	0.025
	Modelled	85.000	0.006	0.040

Site	Date	Discharge (Q, m ³ /s)	Water Slopes – surveyed and estimated for modelled	Manning Resistance (n)
New Forest Canal	21/12/2010	0.247	0.006	0.027
	13/12/2011	0.216	0.006	0.027
	Modelled	0.075	0.006	0.027
Dingleydale River	13/07/2011	0.441	0.0003	0.170
	14/12/2011	0.223	0.0002	0.250
Dingleydale Canal	13/07/2011	0.248	0.0001	0.010
	14/12/2011	0.207	0.0001	0.010
	Modelled	1.200	0.0001	0.010

Table 9.5 Rating coefficients for Equation 3.1

Site	Discharge (Q, m ³ /s)	Rating Coefficients		
		<i>a</i>	<i>b</i>	<i>c</i>
Champagne	All	0.724	0.122	0.000
New Forest River	All	0.669	0.246	0.000
New Forest Canal	All	1.154	0.520	0.000
Dingleydale River	All	0.659	0.085	0.500
Dingleydale Canal	All	0.874	0.434	0.000

9.2.6 Flow gauge installation

Flow gauges were installed during the December 2011 site visits. The river gauges consisted of fixing a wooden pole to the river using steel square sections and thereafter fixing the gauge plates to the wooden pole. The flow gauges for Champagne and Dingleydale are shown in **Figure 9.7** below.



Figure 9.7 Installation of River Flow Gauges

The canal gauges consisted of a gauge plates being attached to the canal bed. The Champagne and Dingleydale canal gauges are shown in **Figure 9.8**.



Figure 9.8 Installation of canal flow gauges

After installation, the gauge plate levels were surveyed relative to the rating cross-section. This was done so that the gauge plate readings could be related to the flow depths at the rated sections and thus the flow rates, using the discharge-depth relationships. The gauge plate levels relative to the rated cross-section are provided in the plots in section 9.1.7.

9.2.7 Cross-sectional profiles

Cross-sectional profiles along with the measured flow depths and gauge plate depths and the rating data and functions for each site are provided from **Figures 9.9 to 9.18**.

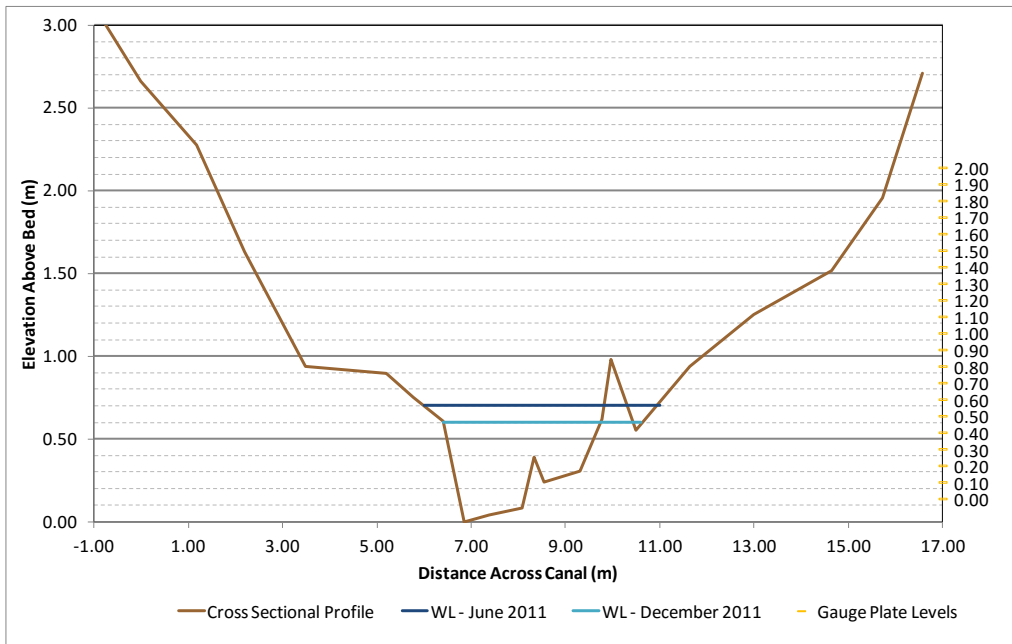


Figure 9.9 Cross-sectional profile for Champagne site showing water and gauge plate levels

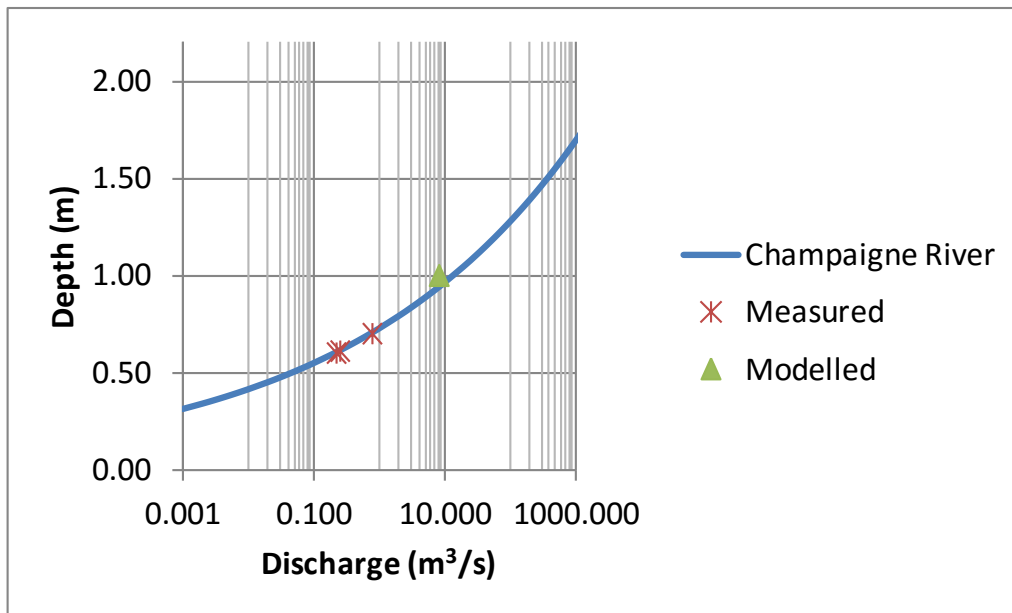


Figure 9.10 Measured and modelled rating data and functions for Champagne site

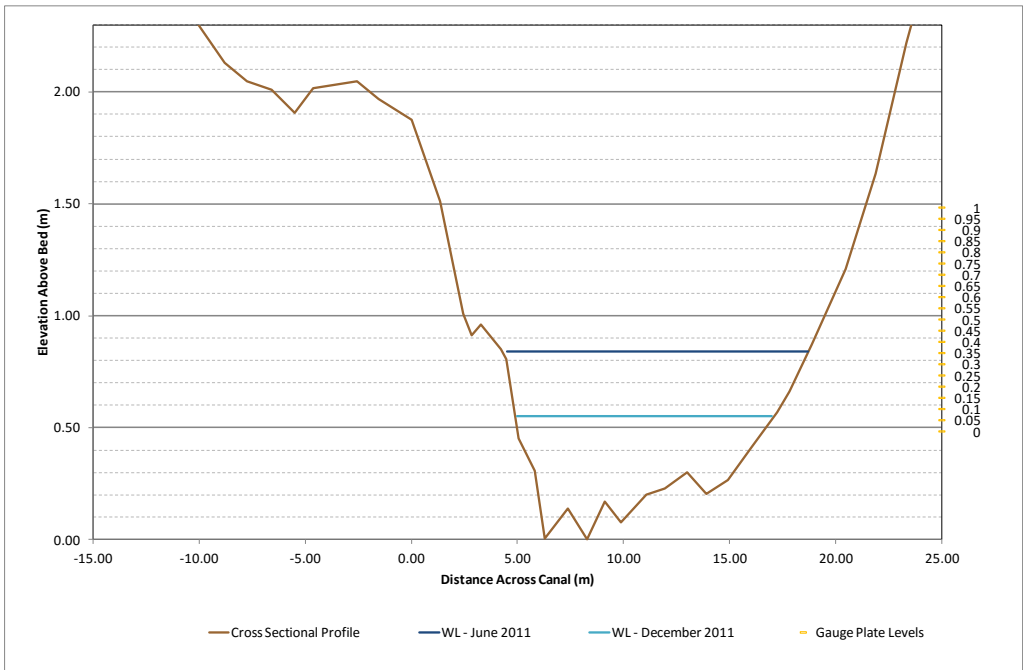


Figure 9.11 Cross-sectional profile for New Forest river site showing water and gauge levels

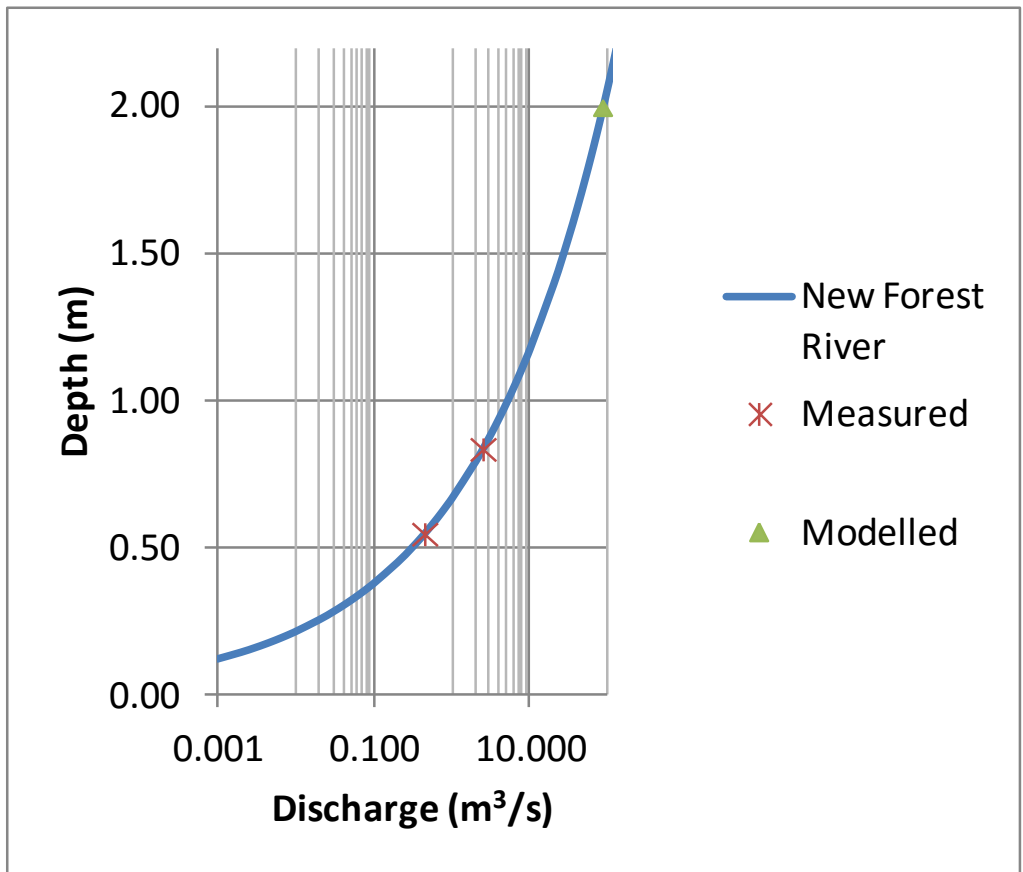


Figure 9.12 Measured and modelled rating data and functions for New Forest river site

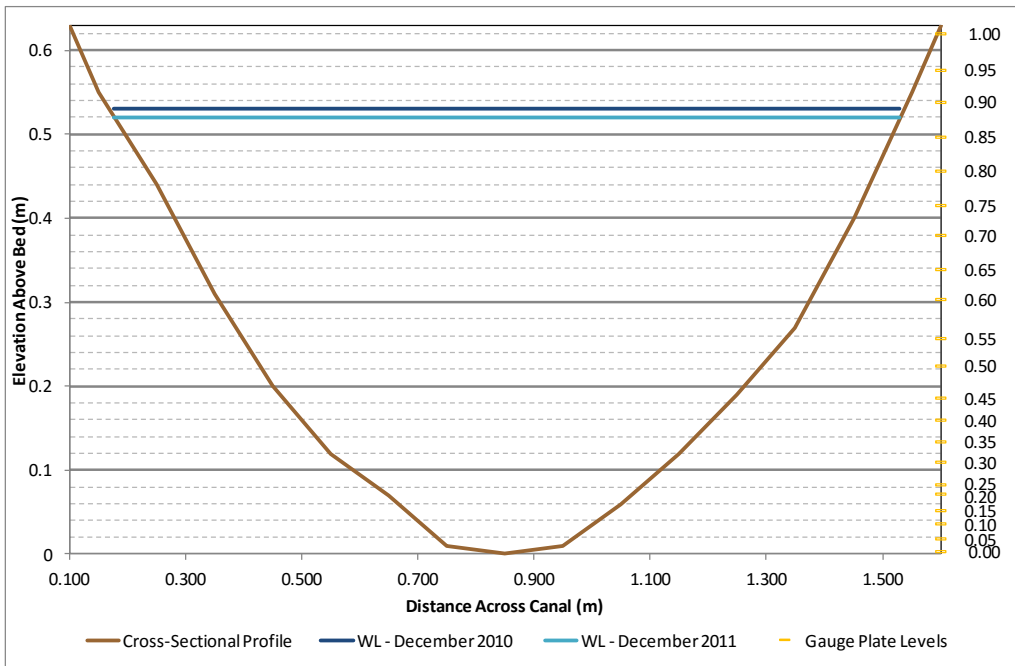


Figure 9.13 Cross-sectional profile for New Forest canal site showing water and gauge plate levels

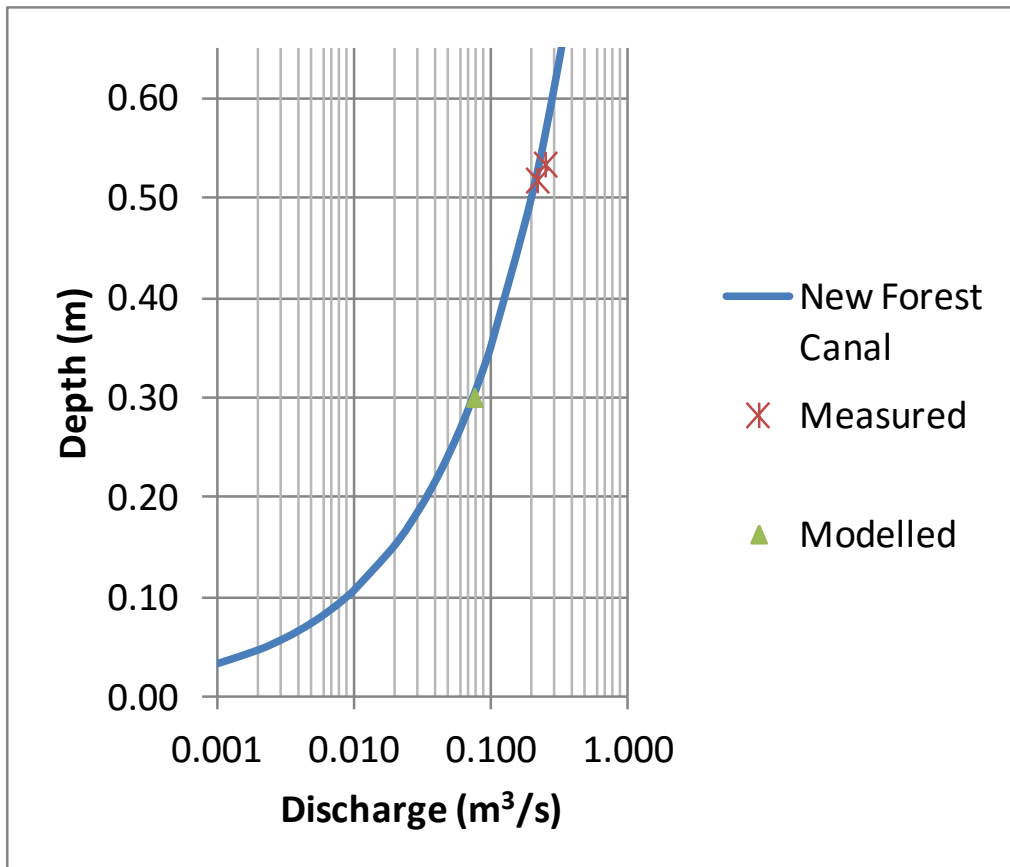


Figure 9.14 Measured and modelled rating data and functions for New Forest canal site

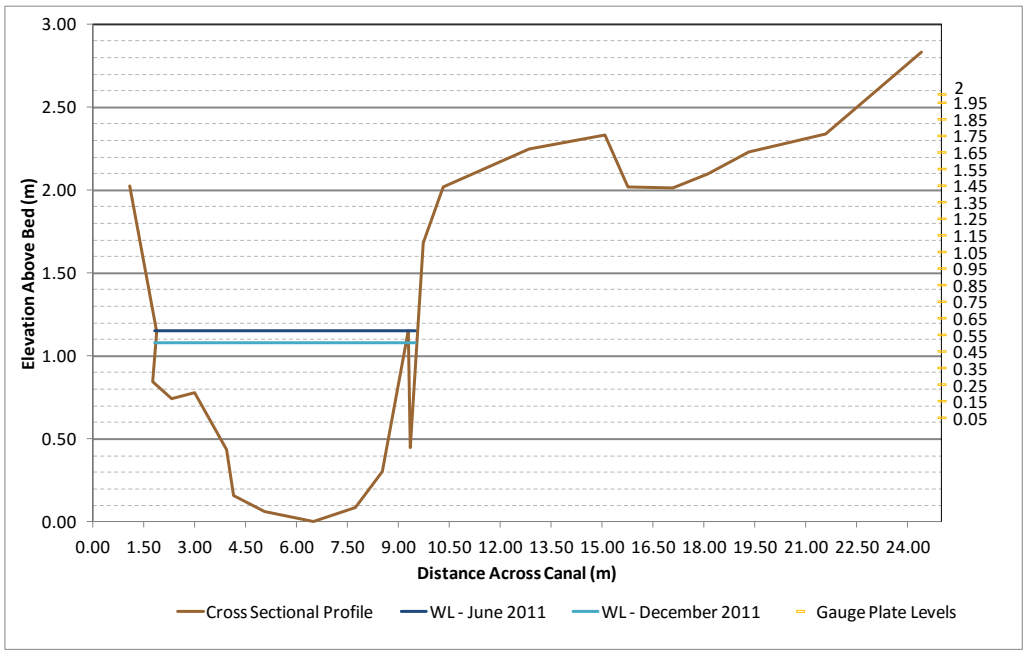


Figure 9.15 Cross-sectional profile for Dingleydale river site showing water and gauge plate levels

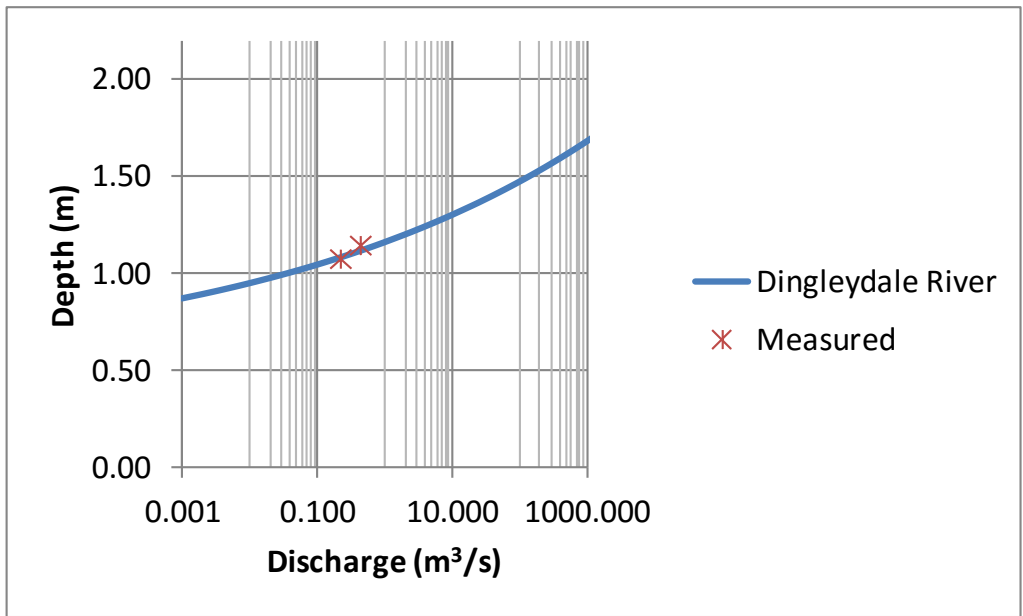


Figure 9.16 Measured and modelled rating data and functions for Dingleydale river site

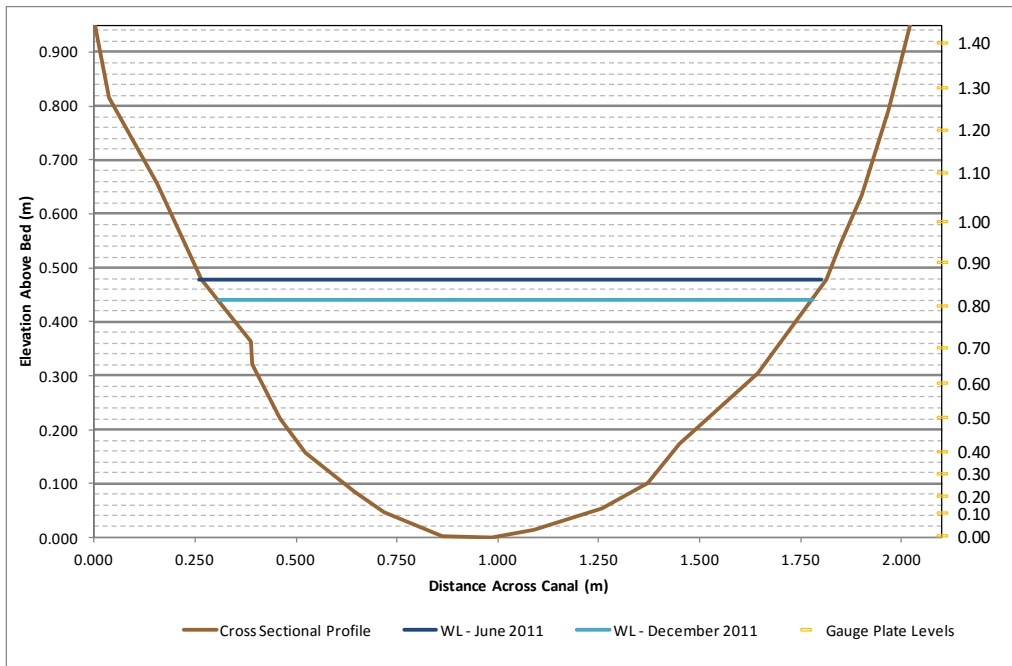


Figure 9.17 Cross-sectional profile for Dingleydale canal site showing water and gauge plate levels

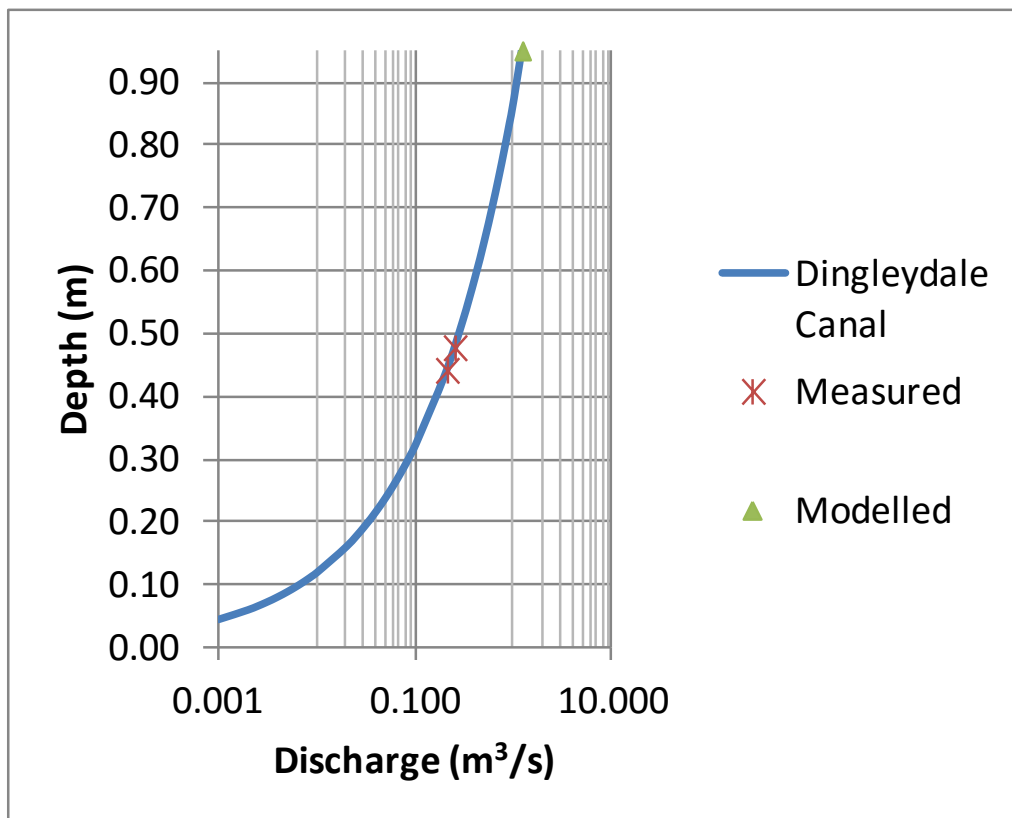


Figure 9.18 Measured and modelled rating and data functions for Dingleydale canal site

10 INFORMATION SHARING AND MANAGEMENT STRUCTURE

For the successful implementation of the DSS, stakeholders in the Sand-Sand River catchment must be actively involved and have direct access to information. A website has been developed as part of this study as an information sharing mechanism. In addition, a System Operating Forum was established to assist in implementing the operating rules and assist water managers with information that will enable sustainable operation of the system.

10.1 INFORMATION SHARING

As a means of sharing information both the medium term and short term operation information have been incorporated and added into the real time reporting system to display information on a website. The information on rainfall, river flows and weather forecasts is published automatically, while short-term and long-term model information is published on weekly and monthly basis. Information produced has been presented and discussed with the Sabie Water Forum and the Sabie River Steering Committee and with various stakeholder representatives in the catchment. Information that is being generated by the system is designed to support the process of decision making; (i) on the level of restriction to place on water users in the catchment over the next few months to a year, (ii) the amount of water that should be released from the dam on a short term basis and (iii) whether all water users can be supplied in the short-term or whether further restriction needs to be implemented or whether the restriction can be lifted on a short-term basis. Information is disseminated and shared through website, email or SMS system. An example of the web page is provided in **Figure 10.1**. The following information is published on the system from the webpage: http://crocdss.inkomaticma.co.za/SABIE_WEB/sabie_site/.

- Home page providing overview of the system (location of real time rainfall stations and flow gauges);
- Weather information in both recorded and forecasted format;
- Volume of water stored in the Inyaka Dam; Rate of release of water from the Inyaka Dam;
- Rate of release of water from the Inyaka Dam (**Figure 10.2**);
- Long-term probability projections of storage levels for Inyaka and Da Gama dams (**Figure 10.3**);
- Quantity of water being transferred by the BTP as direct supply to domestic users;
- Flow in the Sabie River at the flow gauging station at Emmet;
- Water supplied for domestic and irrigation abstraction downstream of the Inyaka Dam and from the canal at Albany and downstream;
- Ecological requirements at EWR 3 (upstream of Kruger Gate river flow gauge) and EWR 8 (downstream of Exeter river flow gauge);
- The flow required at the Kruger Gate gauging station (X3H021);
- The flow required at the Exeter gauging station (X3H008).
- The reports, presentations and minutes are also presented on the website.



Figure 10.1 Snap short of the website home page



Figure 10.2 Short-term decision- dam releases published on website



Figure 10.3 Medium-term decision- dam storage probability projections published on website

10.2 MANAGEMENT STRUCTURE

The Sabie System Operating Forum was established as a consultative technical body, linked to the greater Sabie River Forum as a sub-committee, which provides the mechanism for interaction, exchange of operational information and coordination of operational activities for the Crocodile East River System. ICMA will chair the operating forum while DWA: Systems Operation will provide ICMA with technical and financial assistance where need be to ensure continual operation of the system. The following information and decisions are required on monthly **Table 10.1** and weekly basis (**Table 10.2**). Full membership list of System Operating Forum is presented in **Table 10.3**

Table 10.1 Monthly information needs and decisions required

INFORMATION NEEDS	DECISIONS REQUIRED
Water Orders and Use (demands)	Review of Prevailing Catchment conditions
Report Back on weekly operations	Review Long term model output
Prevailing catchment conditions	Review year-to-date Water Use vs Order
Scenarios	Review Demands
	Possible Restriction Scenarios
	Data and information Exchange
	International Obligation implementation
	Reserve Status

Table 10.2 Weekly information needs and decisions required

INFORMATION NEEDS	DECISIONS REQUIRED
Prevailing Conditions	Dam Releases
Short Term Forecast of expected conditions	Short term restrictions on users
Short term water demands	

Table 10.3 System Operating Forum Members

Full Members of Sabie River Operating Committee:

		Proposed Member
- ICMA	Chair Secretary I&P	Brian Jackson Tendai Sawunyama ICMA
- DWA WRPS		Beason Mwaka Celiwe Ntuli
- DWA NWRP		Neil van Wyk
- DWA Mpumalanga (Nelspruit)		Kenedy Mandaza Sampie Shabangu; Director Water Services
- DWA Infrastructure Branch		Johann van Aswegen, William Matsabe
- Mpumalanga Dept. Agriculture		Amos Msimango Marius van Rooyen
-Sabie River Farmers Association		Reuben Leyane
- Sabie Irrigation Board	Chair Secretary Technical	Izak Fick
-White Waters Irrigation Board		Eric Van Dijk
- Kruger National Park		Freek Venter Robin Peterson
- Mpumalanga Tourism & Parks Agency		
- Sabi Sand Game Reserve		Michael Grover
- Mbombela Municipality	Technical Services	Carol Zulu Pinke Hermanus
- BBR Municipality	Technical Services	Rogers Baloyi
- BBR Water Board		E Radingwana (Director)
- Thaba Chewa Municipality		Albert Fourie

Observers:

- AWARD		Sharon Pollard
- LIMA:		
- ICMA Marketing		Sylvia Machimane
- Ehlanzeni District Municipality		Piet Du Toit
- Ara-Sul		

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 CONCLUSIONS

The concept of the DSS developed as part of this project is to integrate data, technology (hydrological, hydraulic and systems models), and encourage communication between system operators and stakeholders. The Real Time Decision Support Systems are developed to promote efficient use of water resources, protect the source of water from failing and empower users to participate in water resources management (DWA, 2010). These solutions, if implemented effectively, will reduce water wastage due to operational inefficiencies.

For the Sabie River Decision Support System, three models were integrated, a rainfall-runoff model (Sawunyama and Mallory, 2012), the WAS model (hydraulic model) (Benadé et al, 1997) and WReMP model (Mallory *et al.*, 2011). In the case of hydraulic modelling, existing unsteady flow computer models such as ISIS, Mike11, PROCAN and the Water Administration System (WAS) were evaluated (DWA, 2003). The unsteady flow models have drawbacks in the sense that they are very data intensive, need a person with a good hydraulic background and experience to operate and tend to be more unstable compared to steady state models given the erratic runoff events within the catchment and thus WAS model was chosen. The problem that had to be solved for the Sabie River was the calculation of real time releases from the Inyaka Dam to satisfy ecological Reserve requirement and taking inflows, seepage return flows, abstractions, evaporation losses, seepage losses and evapo-transpiration losses into account.

The Annual allocation model used to develop operating rules of the dams deviates from the methodology currently used in the Water Resources Planning Model (WRPM). The short-coming of the WRPM is that it does not take cognizance of the antecedent conditions in the catchment when determining an annual allocation. While the WRPM approach is acceptable in catchments with large storage relative to the catchment's mean annual runoff, it is overly conservative in catchments where the water availability during the dry winter months is very closely correlated with rainfall during the summer months. While the current operation of the Sabie River is based on an annual allocation for all users, the option to impose restrictions during the course of the year is also available in the DSS.

The development of a real time DSS requires sustainable gauging infrastructure development in the catchment area and reliable monitoring system in place for monitoring river flows and pumped abstractions. An effective DSS depends on an entire decision making framework which consists of the operational environment, policy, institutional arrangement, cooperation and coordination between different sectors, decision support tools, and physical infrastructure and enforcement mechanisms. Stakeholder engagement and capacity building is a key element in the development and implementation process. The developed DSS system will assist in water resource management and operation in a sustainable and transparent way and ensure that users do not abstract water to which they are not entitled and also ensure that the system is operated in a sustainable manner. The DSS will be a useful tool to assist the water managers in ensuring that flow for the environmental flow requirements for the Kruger National Park and Mozambique remains on the river and is not abstracted.

11.2 RECOMMENDATIONS

The following recommendations are made as a result of this study:

- The DSS integrates data, technology (hydrological, hydraulic and systems models), and encourage communication between system operators and stakeholders and therefore should continue to be operated to ensure that, *inter alia*, the ecological Reserve in the Sabie/Sand catchment is met.
 - Rating functions and gauge plates which were installed as part of this project need to be upgraded by installing data loggers and telemetry systems.
 - Additional rating data is required as the current data is too coarse which results in poor confidence of the rating functions. Further hydraulic data collection is recommended to improve the rating function confidences.
 - Sustainable gauging infrastructure development in the catchment area and reliable monitoring system for rainfall, river flows and pumped abstractions is prerequisite.
-

12 REFERENCES

- Benadé, N, Annandale, J, Van Zijl, H (1997). The development of a Computerised Management System for Irrigation Schemes. Water Research Commission Report No. 513/1/97. Water Research Commission, Pretoria.
- Department of Water Affairs (2010) The Development of a Real-Time Decision Support System (DSS) for the Crocodile East River System, Report by DHI SA and WFA Consulting for the Department of Water Affairs, Pretoria, RSA.
- Department of Water Affairs (2011) Bushbuckridge Water Availability Assessment, Inkomati Licencing Project.
- Department of Water Affairs and Forestry (1994). Report No. P.X300/00/0194. Water Resources Planning of the Sabie River Catchment. Feasibility Study for the First Phase Development of the Water Resources of the Sabie River Catchment. Chunnett, Fourie and Partners, Pretoria.
- Department of Water Affairs and Forestry (1995). White Paper WP D-94. Report on the Proposed Sabie River Government Water Scheme (First Phase: Injaka Dam and Bosbokrand Transfer Pipeline).
- Department of Water Affairs and Forestry (2003) Sabie River Catchment: Operating Rules and Decision Support Models for Management of the Surface Water Resources. Report No. P. X300/00/3802.
- Department of Water Affairs and Forestry (2009a). Inkomati Water Availability Assessment: Hydrology of the Komati River. Report no. P WMA 05/X22/00/1408.
- Department of Water Affairs and Forestry (2009b) All towns reconciliation study: Bushbuckridge Municipality
- Hughes, D.A. and Mallory, S.J.L. (2008) "Including environmental flow requirements as part of real-time water resource management." *River Research and Applications* 24(6), 852-861.
- Mallory, S.J.L, Gerber, A, Cai, R. Stochastic analyses for the operation of unregulated catchments. Paper presented at the 13th South African National Hydrology Symposium, 2009.
- Mallory and Sawunyama (2012) Linking of daily and monthly hydrological time series for use in monthly water resources models in support of the determination of ecological water requirements. Water Research Commission Report No: K5/1979.
- Mallory S.J.L, Odendaal P, and Desai A (2011) The Water Resources Modelling Platform: Version 3.3. User Guide. Available at www.waterresources.co.za.
- Mallory S J L, Desai A, Odendaal P (2011). The Water Resources Modelling Platform. User Guide Version 3.3.
- Smithers J C and Schulze R E (1995). ACRU Agrohydrological Modelling System. User Manual Veriosn 3.00. Water Research Commission, Pretoria, Report TT70/95.