METHODS AND SOFTWARE FOR THE REAL-TIME IMPLEMENTATION OF THE ECOLOGICAL RESERVE – EXPLANATIONS AND USER MANUAL

Report to the
Water Research Commission

by

D A Hughes, S J L Mallory & D Louw
Institute for Water Research, Rhodes University and
Water for Africa

WRC Report No 1582/1/08
ISBN 978-1-77005-716-6

July 2008

Table of Contents

List of Figures

List of Tables

ACKNOWLEDGMENTS

The authors are very grateful for contributions made to the ideas expressed in this report by a number of individuals involved in both research and water resource management practice. Toriso Tlou of Water for Africa was originally a team member and contributed to the original project proposal and terms of reference. While his later participation was limited due to other commitments, his contributions are duly acknowledged.

The members of the Water Research Commission Reference Group are thanked for their guidance and support:

Dr Stanley Liphadzi	WRC, Chairman of the Reference Group
Dr Steve Mitchell	WRC
Mr Neil van Wyk	DWAF, NWRP
Ms Barbara Weston	DWAF, RDM
Ms Wendy Ralekoa	DWAF, RDM
Dr Bison Mwaka	DWAF, WRPS
Mr Norman Ward	DWAF, KwaZulu-Natal Region
Ms Christa Thirion	DWAF, RQS
Dr Neels Kleynhans	DWAF, RQS
Dr Deon Terblanche	SAWS

The DWAF staff members who attended various specialist project meetings in Durban and Pretoria are also thanked for their helpful comments and criticisms:

J Perkins, N Ward, M Pillay, C Tylcoat, D Brune, S Shange, B Mwaka, W van de Westhuizen, R Cai, T Mbhele, S Mabaso, P de Wet, G Daniell

For a project of this nature it was always important to obtain direction and critical comment from water resource management practitioners, especially those who are directly familiar with the real situations.

Even before this project was conceived, there were a number of discussions about the implementation of the Reserve between some of the project team and various DWAF staff. We would especially like to thank Elias Nel and Harrison Pienaar for their contributions.

EXECUTIVE SUMMARY

This report represents the final report on the Water Research Commission funded project K5/1582:

‘Development, testing and installation of a real-time ecological Reserve implementation method for the Thukela River’

While the project title refers to the implementation of the ecological Reserve, it should be emphasised that the project and its results are about real-time water management that includes an allowance for the Reserve as well as water users. In that respect the project has been about developing methods whereby the analyses that are typically undertaken using a water resource systems yield model can be given effect to in a real-time operational system.

The project has generated a number of deliverable reports that contain the full technical details of all methods and software that have been developed, as well as the revisions that occurred as a result of interactions between the project team and potential users. This final report does not repeat all of that information, but summarises the principles underlying the developments, explains how the real-time systems are established for a specific catchment and acts as a user manual for the use of software that can be used to apply the real-time systems. The title of the project specifically refers to the Thukela River basin. While the developments were based on the situation within the Thukela, the systems are generic and should be flexible enough to be applied in almost any water management area. Sections 7 and 8 of this report highlight some of the relevant issues for the Thukela basin as well as for the Kouga basin in the Eastern Cape Province.

The introduction to the report attempts to establish some of the principles behind the links between Reserve determinations (the design phase) and the incorporation of the Reserve into real-time operational management. It also highlights the differences between implementation situations, notably where there is storage that can be used to control flows and where there is no storage and all ‘users’ are reliant upon run-of-river flows. This section emphasises the need for operational rules in all situations, where these rules can include patterns of releases from reservoirs (perhaps the conventional understanding of the term ‘operating rules’), water user supply curtailments based on the current state of storage, as well as supply curtailments based on the estimated natural flow condition in the river. The latter may not exist due to a wide range of abstractions, return flows or other modifications, but nevertheless represents the best measure of water ‘availability’ that is common to all water users. Estimates of the natural flow conditions are also the ideal trigger for setting the ecological Reserve requirements as the natural flows are used in the Reserve determination process.

The introduction emphasises the differences between the low and high flow components of the ecological Reserve and the fact that they will always be managed in separate ways.

The approaches that have been developed during this project are supported by new software that has been included as part of the SPATSIM framework. SPATSIM was chosen as it already includes many of the analysis methods that are used in Reserve studies and has an established interface with a database structure that can store a wide variety of different information. While applications of the methods and software require

specialists to setup and calibrate, the real-time operational use of the software has been designed for non-specialists who do not have to have a full understanding of the SPATSIM framework.

Section 2 provides the details of how an application of the low flow management system is established. The system makes use of a real-time application of the Pitman rainfall runoff model to simulate the monthly natural flow conditions for defined Reserve management areas. The simulations are based on real-time collection of rainfall data from reporting stations. The report highlights the current difficulties in obtaining rainfall information with consistent reliability. While this issue represents a stumbling block to the successful implementation of the software, it does not mean that the method should be abandoned and it is expected that the reliability of real-time collection of rainfall data will improve in the near future. In fact, the establishment of the proposed approach to managing water resources provides strong motivation for the improvement in rainfall data collection systems.

The second component of establishing the low flow management system is the 'calibration' of all the different operating rules including the Reserve targets, reservoir releases and curtailments levels and run-of-river curtailment levels. These are established using a water resources systems yield model that allows the water management agency (in collaboration with the water users) to determine operating rules that achieve a water balance at all times and are socially, economically and environmentally equitable and sustainable. Later in the report it is noted that while systems yield models are designed to achieve this objective, the relevant social and economic measures to assess the impacts of various operating rule scenarios are not well developed at this stage.

Section 3 covers the design and setting up of the high flow management system. It became very clear during the project that establishing a practical real-time high flow system is a great deal more difficult than for low flows. The report refers to some existing methods can could be used to account for attenuation and losses, as well as tributary inflows in the design of high flow releases. However, the main part of section 3 focuses on the design of the real-time triggers for high flows. While, the report has offered a solution and the software to apply that solution, it is clear that it is not an ideal solution and it may be difficult to apply in many cases. Part of the problem lies in obtaining real-time trigger information quickly enough to analyse and input into the decision making process before a release should be made. The main problem lies in trying to make releases to match future tributary inflow events downstream. Matching these events is the ideal approach from both a water management point of view (less water needs to be released to achieve a specific downstream peak target), as well as an environmental point of view. However, matching these events requires a reliable 'forecast' of future flow conditions within the catchment. The project team was unable to identify a suitable and reliable 'forecast' method and eventually settled for an approach that is less than perfect, but is integrated with the other parts of the real-time operational system. This issue will need to be re-visited if the management of high flow releases is to be improved in the future. It is worth noting that there are many situations where the Reserve high flow requirements are unlikely to be completely managed due to either the lack of suitable release mechanisms (valves or gates, etc.) or because the size of the reservoir storage is such that most of the larger high flows will generate spillage and therefore high flow events downstream.

Sections 7 and 8 provides some further details about how the low flow component of the system has been 'calibrated' for two example basins; the Thukela and the Kouga. The Thukela is dealt with in some detail as this was used as the main example in the project and a number of discussions about the operating rules were held with regional DWAF staff. It became apparent during the project that the ideal approach to establishing operating rules is often constrained by what is possible in practice. This is in turn constrained by either a lack of capacity within the regional water management structures or a lack of the supporting legislation that would be required to enforce operating rules and supply curtailments. It was frequently noted that when the legislation concerning compulsory water use licensing is given effect to, the situation should improve and it should be possible to exercise greater control. In the absence of compulsory licensing many users are 'getting way with' uncontrolled abstractions, while other users bear the brunt of the controls that can be managed to achieve the defined ecological Reserve targets. Clearly, from a basin-wide point of view, this is not an equitable and sustainable solution and needs to be corrected as soon as possible.

Both the Thukela and Kouga examples illustrate the importance of accurate and reliable data in setting up the various models that lead to the design of the operational system. These data include simulations of the natural hydrology (and therefore the total available water resource and its distribution in time and space), existing patterns of water use (including source of water, seasonal distributions, variations over years and what the water is used for), existing patterns of return flows or discharges to the river, water management infrastructure (including small farm dams, large reservoirs and associated release capabilities, canals and distribution networks). Although not specifically addressed as part of the research undertaken for this project, information is ideally required about the social, economic and environmental benefits of all water use, as well as the impacts of a reduction in supply below the normal.

This latter point is further emphasised in the final section (9: Conclusions and recommendations), which also refers to some of the constraints that are likely to hinder the use of the proposed methods in practice. This section also refers to some of the consequences of changes in future patterns of climate and therefore water availability. Some recommendations are made about how to proceed with the use of the approaches under such situations.

This report has said very little about the issue of monitoring. There are essentially three types of monitoring that are required. The first relates to water users and monitoring their compliance with the conditions of their abstraction licenses. This is probably the most difficult and requires quite substantial resources on the part of the water management agency. Community self-monitoring should therefore be encouraged wherever possible. This would involve the community of water users monitoring the compliance of individuals within the community. The other two types of monitoring refer to the Reserve and involve determining whether the flow requirements of the Reserve are being met (flow monitoring) and whether those flow requirements are achieving the ecological objectives that were defined as part of the design (biological monitoring). Both of these involve long-term monitoring programmes and various recommendations have been made in the past as part of Reserve determinations undertaken for specific river systems.

In general terms the members of the project team are satisfied with the outcomes of the project and are reasonably confident that the methods and software that have been developed are based on sound principles and can be applied in practice. This level of confidence is higher for the low flow components than for the high flow components. The project team is satisfied with the initial responses to the developed approaches from the water resource management community and their inputs were valuable. However, the project has failed to properly test the developed systems in a real situation and this need to be addressed in the near future.

Internationally, there appears to be an increasing level of interest in the implementation of environmental flows as part of integrated water resource management. It is therefore important that contributions from South Africa are communicated to other countries so that our approaches can be appraised and considered together with other suggestions.

The members of the project team are also involved in a Department of Water Affairs and Forestry project on 'Development and pilot implementation of a framework to operationalise the Reserve', which began at the end of 2006. There are clear overlaps between the WRC project just completed and the DWAF project that has just started. It is important that the concepts, methods and software that are contained within this report undergo further critical appraisal and development within the DWAF project. The DWAF project is designed to include a great deal more about the social and economic issues (see earlier comments in this section) and it is anticipated that these will then be better integrated with the Reserve and operating rules that have dominated this report.

The report has highlighted four major areas where improvements are required in information, data availability or water management practice for the methods that have been developed to be effective. The major information requirement is related to the socio-economic effects of different operating rules on different water sectors. This issue is being addressed as part of the DWAF RDM Implementation project referred to above. The main issue regarding data availability relates to the availability of rainfall data which is able to represent spatial variability within basins, is reliable and that can be accessed rapidly for real-time water management. This is a requirement for South Africa that is long over due, while the reality is that the situation is worse now than it was in the past. A related issue is the need for improved short-term rainfall forecasting techniques. Finally, there is a need for improvements in water management practices that will enable operating rule decisions (such as the implementation of abstraction curtailments) to be effective. The future introduction of compulsory licensing, where licenses incorporate supply curtailment conditions, should go a long way towards satisfying this requirement if it is possible to monitor and regulate abstraction practices.

The final part of the 'Conclusions and Recommendations' section refers to two separate training requirements. The first would be designed for the specialists who may be tasked with establishing the system for a specific water management authority, while the second would be designed for the personnel of the water management authority who would be tasked with running the real-time system operationally.

Training insetting up the system would be directed at personnel who are already reasonably familiar with the application of rainfall-runoff models and system yield models. The focus of the recommendations for training is on the low flow component of the real-time operational system and additional training would be required for the high flow component. Depending upon the existing level of expertise and experience of the trainees, the training session would probably take between 3 and 5 days.

The amount of time required for training in the operational use of the low flow management support system will be much less than for setting up the system. It is assumed that such training could be completed in approximately 1 to 2 days. The focus in this training would be on the use of the software and the interpretation of the results. The assumption is that the material being used for training would be directly relevant to the trainees, i.e. a system that has been set up for their specific water management area would be used.

1. INTRODUCTION

The main purpose of this document is to provide guidance in the setting up and use of the methods and associated software that have been developed to assist with implementing the Ecological Reserve as part of real-time water resource management. It is, however, necessary to start with some introductory remarks about the Ecological Reserve, how it is perceived to fit in with real-time water management and the background to the software development. It is not the intention of this document to provide full details and explanations, but to include brief summaries to ensure that the later parts of the document are placed into the correct context.

There are essentially two main components involved with the implementation of the Reserve. The first is associated with the allocation of water rights through licensing, while the second is concerned with managing those rights in real-time. The former is largely a design process that involves ensuring that the allocations (and any associated restrictions or operating rules) are possible given the available natural resource and supply infrastructure (reservoir storage, etc.). The latter is concerned with ensuring that users comply with their license conditions and do not abstract more water than has been allowed for. While an allowance for the Reserve is required in both implementation processes, this project has been concerned with the latter. However, the analyses and decisions associated with water allocation planning and licensing are required before any real-time management system can be put into place. This issue will be discussed in more detail later.

1.1 The Ecological Reserve and its implementation as part of integrated water resource management.

In South African terms, the quantity component of the ecological Reserve for rivers is defined as a set of flows associated with a range of assurances, where assurance is the equivalent of the percentage time that any specific flow is expected to be equaled or exceeded. The assurance rule tables are therefore directly equivalent to flow duration curves that are frequently used to summarise time series of hydrological data. While there are many different methods that can be used to determine an ecological Reserve, the outputs generated in South Africa are always the same and have been standardised. Table 1 provides an example of the typical output from an ecological Reserve determination as distributed by the RDM (Resource Directed Measures) Office of DWAF (Department of Water Affairs and Forestry) after a Reserve has been approved and signed off. The example provided lists the requirements in $m^3\ s^{-1}$ mean monthly flow, while it is also quite common for these tables to be generated as monthly volumes (in $m^3 * 10^6$).

While this document does not include any details of the various methods of determining an ecological Reserve, it is important that some of the basic concepts are explained so that these can be understood in the context of implementation.

1.1.1 Distinction between low flows and high flows

Reserve low flows are assumed to be the more or less continuous (at least in rivers that have permanent flow under natural conditions) background flows that change relatively slowly in response to medium to long term changes in climate patterns. A further assumption is that changes within a month will be relatively small. With reference to

Table 1 it can be seen that the requirements for dry season months are lower than for wet season months. Within a calendar month, the lower values (70% to 99%) are appropriate for drought periods, while the higher values (10% to 30%) would be appropriate for wet periods.

Table 1 Example of a Reserve definition 'Rule' table (data are given in $m^3 s^{-1}$ mean monthly flow).

[illegible]						[illegible]				
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

High flow requirements are defined during a Reserve determination as a set of events that are expected to perform specific critical ecological or geomorphological functions. They are typically defined by a range of peak flows and a duration (Table 2, for example). The assumption is that the lower range of the peaks would apply during naturally dry conditions and that the higher range would apply during wet conditions. It is further assumed that they would be required only when natural floods are expected to occur. The translation of these detailed high flow event specifications into either volumes or mean monthly flows (Table 1) is required to make them compatible with the low flow requirements and to allow them to be used as input to a yield assessment model that operates on a monthly time step. It must be recognized that the required volume is not evenly distributed throughout the month, but is concentrated in a much shorter duration.

Table 2 An example of a high flow definition table generated during a Reserve determination.

Component	Flood Classes m^3/s					
	I	II	III	IV	V	VI
Fish	10					
Invertebrates	10-25	Low+10		140		
Vegetation	10-25	20-60	60-140	140-220		
Geomorphology			60-139	140-233	233-241	441-510
Integrated	10-24	25-59	60-139	140-220	221-440	441-510
Geometric Mean	17	42	92	175	320	474
Recommended Floods						
No of events for B/C PES (Alternative scenario)	6 (O N, D, F, A, S)	4 (N, D, F, M)	4 (D, J, M, N)	1 (J)	1 (F)	1 in 3 years
Daily average (m^3/s)	15	40	90	120	250	
Duration (days)	4	4	6	7	7	

1.1.2 The timing of Reserve flow requirements

The assurance rule tables (Table 1, for example) only specify how frequently flows of a specific magnitude should be equaled or exceeded, they do not indicate when such flows should occur. Clearly, in any real-time implementation method further information is required so that the required flow for a specific day or month can be determined. The basis of a suitable method is different for low flows and high flows.

With respect to low flows, the assumption made during a Reserve determination is that the patterns of flow variation for the Reserve requirements should reflect the natural flow variations. In simple terms, when a natural drought is occurring, the lowest Reserve flows should be applicable, while the higher Reserve flows should apply during naturally wet periods. The most appropriate method of achieving this objective is to ‘know’ what the natural flow would have been, look that flow up in the natural flow duration curve (third block in Table 1) and select the appropriate Reserve low flow (second block in Table 1) for the same % point and calendar month. For example, if the natural flow in an October month is estimated to be 0.8 $m^3 s^{-1}$, the % point is between 60 and 70%. Interpolation in Table 1 suggests that the Reserve low flow requirement should be about 0.42 $m^3 s^{-1}$. The critical issue from a real-time implementation point of view is that an estimate of the natural flow (or at least the exceedence frequency of the natural flow) would be needed every time a Reserve requirement is to be estimated.

While the information required to trigger the low flow Reserve requirements is a continuous signal of natural flow exceedence frequency, the information required for high flow requirements can be a great deal more complex. High flows are typically either not managed (where there is no infrastructure to control high flow releases) or are managed as releases from reservoirs. To optimize the releases (i.e. to release as little as possible) they should occur at the same time as any inflow events from downstream tributaries. The implication of this is that the optimum method of releasing high flows will rely upon some kind of 'forecast' of what is likely to happen in the near future. This makes the whole problem of high flow releases far more complex and the likelihood of being able to make optimum releases much lower.

1.2 Implementation situations

It is recognized that any method (and software) that is developed for managing the ecological Reserve must account for different water resource development and supply situations. These can be broadly divided up into situations where the water resource manager has some control over the flow rates in the channel through controlled releases from reservoir storage and where the manager has no such control.

In cases where there is no release control the only effective form of management that can ensure that the Reserve requirements will be met is through allocation licensing and monitoring users to make sure that they comply with their license conditions. Water resource yield analyses, based on balancing the naturally available resource, the Reserve requirements and the licensed user requirements will be required to determine license conditions. The real-time implementation process is therefore confined to determining when certain license conditions (i.e. restrictions) will need to be applied to different water user sectors to maintain flows in the river that will satisfy the Reserve requirements. The assumptions in this project are that these restrictions will be linked to the same time series signals (or triggers) that determine the Reserve requirements, i.e. an estimate of the natural flow condition. In these situations only the low flows will be managed as no infrastructure is available to control high flows.

In cases of storage there could be two groups of water users; those supplied directly from the reservoir (either through releases along the channel, or though pumping from the dam) and those who are run-of-river users between the dam site and the Reserve site. The assumptions made in this project are that the users supplied from the reservoir will have license conditions that are controlled by the reservoir level. This means that any restrictions that apply in real-time will be determined by the current and expected future storage state of the reservoir. Downstream run-of-river users will be controlled in the same way as if there was no storage (i.e. through time series signals based on estimates of natural flow conditions). The extent to which high flow releases can be managed will largely depend upon the volume of storage (relative to typical natural flow volumes) as well as the capacity of the available release infrastructure (gates, valves, etc.).

The methods that have been developed during this project have attempted to account for all the possible implementation situations that are likely to occur.

1.3 Background to the software development

At the start of the project it was necessary to make some decisions about the format of the software that would be developed to support the proposed methods. The SPATSIM framework (Hughes, 2004a) has already been used to host many of the computer based models that have been developed to support Reserve determinations and the underlying database structure has been demonstrated to be suitable for storing the type of information that is required for a real-time Reserve implementation process. Exchanging data between SPATSIM and other relevant models (mostly system yield models) has also been demonstrated to be relatively efficient and simple to achieve. It was therefore decided to include the models and data analysis procedures to be developed within this project as part of SPATSIM. However, at the same time, it was recognized that the operational users of the methods could not be expected to learn all the details of running SPATSIM and managing an associated database. It was therefore necessary to ensure that the new software and models could be run without a detailed knowledge of SPATSIM and that they should also be as user friendly as possible.

As will be seen from later sections of this report, there are two main groups of methods and associated software products that are recommended for use. The first group requires specialist input and is **NOT** designed for use by operational management staff. These methods are associated with setting up the real-time operational system. The second group does not require specialist input and are designed for use by operational staff after a limited amount of initial training. These software products have been demonstrated to a group within the KwaZulu-Natal Regional DWAF Office and were considered to be acceptable and not too complex to use.

1.4 Structure of this report

As already indicated, the project involved developing methods for establishing a real-time Reserve operation system, as well as methods for actually running the system. At the same time there are considered to be two distinct components to a real-time system: managing low flows and managing high flows. The report is therefore structured in the same way, with sections that describe the procedures for setting up the low and high flow management components and sections that describe the recommendations for the real-time operation. Necessarily, the sections focusing on the procedures for setting up the system are a great deal more technical than those describing their operational use. In all other respects this report is structured as far as possible as a user manual, concentrating on guidelines for the use and application of the methods. Important specific issues that potential users need to be aware of are highlighted in the report.

The separate report deliverables for the project are listed in Table 3 and the final report contains summaries of the previous reports. In some cases there are slightly more technical details contained within the deliverables than in this final report. All of the deliverables are available from the senior author in electronic format (e-mail address denis@iwr.ru.ac.za) upon request.

Table 3 Project deliverables and any modifications made during the project

Deliverable No.	Description	Status
A	Re-calibrated Pitman model using reporting raingauges.	Completed successfully
B	Develop prototype software package for real-time implementation process (focus on low flows).	Completed successfully
C	Design decision making criteria for RDM and water users and incorporate into the software (focus on low flows).	Completed successfully
D	Regional Office training and evaluation, model assessment and refinement (focus on low flows).	Completed successfully
E	Monitoring of the application of the model (low flows) in real time.	Not completed due to lack of capacity in the Regional Office.
F	Assessment of flood release capabilities and requirements and review of existing methods.	Completed successfully
G	Refinement of real-time high flow release methods and presentation to regional staff.	Not presented to regional staff, but prototype high flow release software has been developed.
H	Development of training materials and user manuals.	This report.

2. SETTING UP THE LOW FLOW MANAGEMENT SYSTEM

There are essentially two linked components to establishing the low flow management system; the process that generates the real-time signals which will be used to trigger the Reserve requirements and the process that establishes the operating rules that are used to determine water user curtailments and any low flow releases required from storage to meet the Reserve.

2.1 Setting up a real-time version of the Pitman monthly rainfall-runoff model

One of the principles of the implementation of environmental flow requirements within a South African context is that temporal variations in Reserve requirements should reflect temporal variations in natural flow. This is a principle that is also widely acknowledged internationally as an appropriate way to ensure that some degree of variability is included in a managed flow regime. Given the expected difficulties of being able to identify gauged flow data that would adequately reflect natural conditions, it was decided that the best approach would be to use a near real-time simulation model to generate the required patterns of natural flow. A further motivation is the fact that the use of the Pitman model for generating natural flows is well established and generally accepted in South Africa. There will always, therefore, be a source of default parameters that can be used to establish the model. However, it should also be noted that the most appropriate parameter set to use is somewhat dependent upon the rainfall data that are used for the main model input. The rainfall data that will be available in real-time will, inevitably, be different to the rainfall data that would have been available in the past and would have been used in the original calibration of the model. These issues are addressed in more detail below.

One of the critical issues to note is that the absolute values of stream flow volume that are generated by the real-time simulation model are not critically important. This is because the signals and triggers used to determine a Reserve flow in any specific month will be based on the percentage points of the flow duration curve. The most important aspects of the simulated flows are the seasonality and the frequency, duration and sequencing of wet and dry periods. The best way to check if the output from the model, using the real-time rainfall data set, is appropriate is to run the Desktop Reserve model with the original natural flows and with the re-calibrated model and to check if the time series of Reserve requirements are broadly similar.

There are several versions of the Pitman model available including the SPATSIM version that includes the revised ground water simulation routines of Hughes (2004b) and Hughes and Parsons (2005), as well as the new official version PITMAN2005. These two versions generate the same outputs for natural flows (checked as part of the WRC Project WR2005), despite having different ways of linking quaternary incremental flows. The SPATSIM version is the one that is used within the real-time procedure, but it will not matter which version is used to establish the revised parameter set that is appropriate to the real-time rainfall data.

The following sub-sections identify the steps required in setting up the real-time version of the Pitman model and illustrate the process with some examples using the Thukela basin. Note that all of the analyses that are recommended (rainfall cross-correlation, time series comparisons, etc.) can be performed with the SPATSIM software.

2.1.1 Step 1: Identifying the real-time reporting rainfall stations

The criteria for selection of the real-time reporting stations are that they should have reasonably complete records for roughly 20 years and should be expected to remain active for the foreseeable future. Further criteria are that they should be able to represent the 'real' rainfall variations over the total basin and at least one of the stations should be applicable to every single quaternary catchment within the basin. In practice the last two criteria might be difficult to satisfy if many of the stations that used to be active have recently closed down or are not generating reliable data. This was the case in the Thukela and the situation is illustrated in Figure 1 which compares the stations open in the year 2000 with those that can be used in real-time. In fact the situation has been revealed to be even worse as some of those that are still open frequently do not report reliable data. Figure 1 illustrates that in the Thukela basin there are no active SAWS (South African Weather Service) stations in the northern areas and DWAF stations need to be used (V3E002 and V3E005).

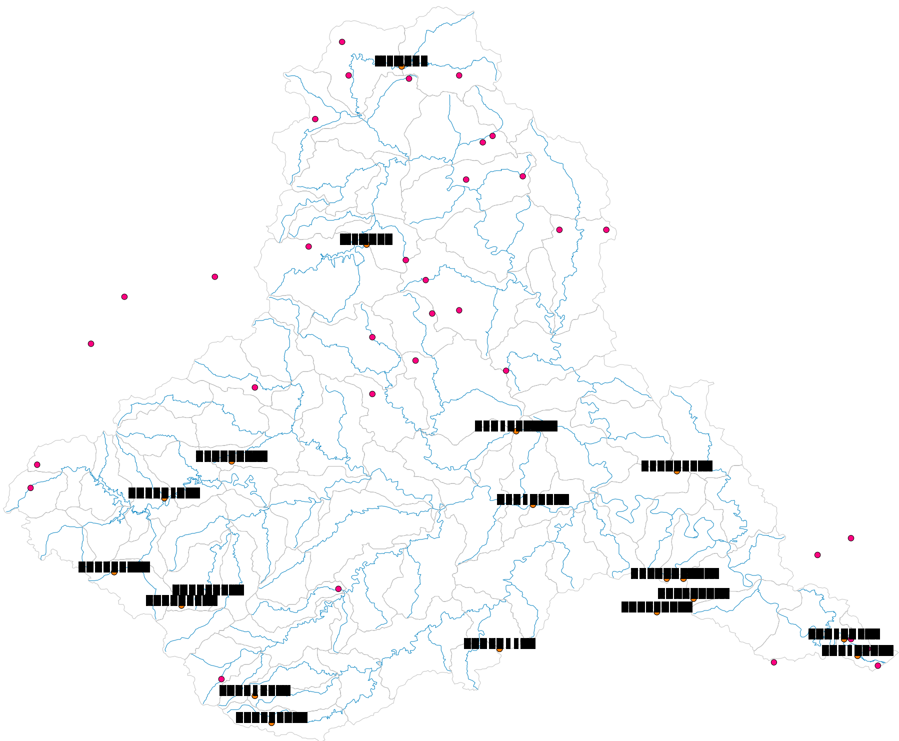


Figure 1 Currently active raingauge stations (named) compared to those active in the year 2000 (unnamed dots)

If there are more stations currently open than might be needed for the modelling exercise, it would be appropriate to investigate the inter-gauge correlation structure and to compare individual gauge records to the WR90 rainfall data (or WR2005 rainfall data when it becomes more widely available).

2.1.2 *Step 2: Select and process the rainfall data to be used for each quaternary catchment model input*

This step involves several sub-steps that are all designed to create the historical records of model input for each quaternary catchment and specify the gauges and weighting factors to be used for the real-time modelling.

The real-time version of the model assumes that the input rainfall will be based on a single gauge which will be patched by an alternative gauge if the preferred gauge has missing data. It is important to recognize that the original WR90 rainfall inputs to the rainfall-runoff model were based on an area averaging procedure using several raingauges (the actual number used depending on the availability of gauges in the vicinity of the different rainfall regions). It has been assumed that for the real-time inputs there will not be enough raingauges available to be able to repeat the process of areal averaging and that single gauges will necessarily have to be used to represent the catchment average inputs. While this is not an ideal situation with respect to providing rainfall inputs to hydrological models, it is likely to be the only practical approach.

Cross-correlation analysis can be used to find the gauge that best matches the characteristics of the WR90 (or WR2005) rainfall data, as well as to identify a group of 5 gauges that are likely to be the most appropriate for patching other gauges and the scaling factors to be used in the patching process. The real-time data preparation software allows up to 5 alternative gauges to be specified for patching missing data. The simple patching process that is used takes successive stations in the list until it finds data for the period that is missing. Each of the patching stations has a scaling factor associated with it.

The following steps summarise the rainfall pre-processing stage:

1. Identify the 'best' individual gauges that can be used to represent the WR90 rainfall data and are therefore appropriate to be used as input to the real-time version of the model.
2. Select up to 5 stations to be used for patching each of the stations and determine linear scaling factors to be used in the patching process.
3. Patch the historical rainfall data for the gauges identified in step 4 for a common period (October 1950 to Present day, for example). These are the data that will be used in re-calibrating the model and should be at least 20 years in length.
4. Copy the appropriate patched station rainfall data to the quaternary catchment rainfall attribute (in SPATSIM) to be used for input to the model.
5. Scale the patched quaternary rainfall data to the same MAP as the WR90 rainfall data for the common period (October 1950 to September 1990, for example).

Table 4 lists the R^2 values for the relationships between the selected stations and the WR90 rainfall data. Tables 5 to 8 list the quaternary catchments in the Thukela basin together with the most appropriate gauge (currently active) and the ratio that corrects the gauge data to the WR90 catchment mean annual rainfall.

Table 4 Reporting gauges selected for quaternary catchment groups

Quaternary No.s	Gauge	R^2
V31A to D	V3E002	0.792
V31E to K	V3E002	0.879
V32A to H	V3E002	0.850
V60A to E	V3E002	0.830
V60F to J	301795	0.782
V12A to F	300067	0.865
V11A to E	299614	0.872
V11F,J to L	299614	0.870
V11G,H;V13A to D	299900	0.882
V11M,12G,13E,14A to E	300067	0.861
V70A to E	268199	0.812
V70F to G	269611	0.664
V20A to C	268352	0.950
V20D to G	269611	0.804
V33A to D	301692	0.821
V20H,J;V60K	302628	0.789
V40A to D	302628	0.872
V50A to D	302628	0.854

Table 5 Rainfall stations and scaling ratios to be used to create the single station inputs to the real-time rainfall-runoff model (catchments V11, v12 and V13)

V11			V12			V13		
Quat.	Gauge	Ratios	Quat.	Gauge	Ratios	Quat.	Gauge	Ratios
A	299614	1.690	A	300067	1.131	A	299900	1.396
B	299614	1.870	B	300067	1.088	B	299900	1.065
C	299614	1.434	C	300067	0.983	C	299900	0.898
D	299614	1.236	D	300067	1.246	D	299900	0.888
E	299614	1.479	E	300067	0.966	E	299900	0.874
F	299614	1.142	F	300067	0.902			
G	299900	1.413	G	300067	0.914			
H	299900	1.077						
J	299614	1.150						
K	299614	1.264						
L	299614	1.023						
M	300067	0.961						

Table 6 Rainfall stations and scaling ratios to be used to create the single station inputs to the real-time rainfall-runoff model (catchments V14, v20 and V31)

V14			V20			V31		
Quat.	Gauge	Ratios	Quat.	Gauge	Ratios	Quat.	Gauge	Ratios
A	300067	0.904	A	268352	0.972	A	V3E002	1.068
B	300067	0.882	B	268352	0.922	B	V3E002	0.997
C	300067	0.976	C	268352	0.904	C	V3E002	0.944
D	300067	0.882	D	269611	0.976	D	V3E002	0.920
E	300067	0.941	E	269611	0.860	E	V3E002	1.014
			F	269611	0.988	F	V3E002	1.092
			G	269611	0.865	G	V3E002	0.905
			H	302628	0.812	H	V3E002	1.147
			J	302628	0.799	J	V3E002	1.037
						K	V3E002	0.944

Table 7 Rainfall stations and scaling ratios to be used to create the single station inputs to the real-time rainfall-runoff model (catchments V32, v33 and V40)

V32			V33			V40		
Quat.	Gauge	Ratios	Quat.	Gauge	Ratios	Quat.	Gauge	Ratios
A	V3E002	1.136	A	301692	0.815	A	302628	1.067
B	V3E002	0.965	B	301692	0.805	B	302628	0.895
C	V3E002	0.879	C	301692	0.843	C	302628	0.981
D	V3E002	0.896	D	301692	0.806	D	302628	0.947
E	V3E002	0.935				E	302628	0.848
F	V3E002	0.890						
G	V3E002	1.034						
H	V3E002	0.870						

Table 8 Rainfall stations and scaling ratios to be used to create the single station inputs to the real-time rainfall-runoff model (catchments V50, v60 and V70)

V50			V60			V70		
Quat.	Gauge	Ratios	Quat.	Gauge	Ratios	Quat.	Gauge	Ratios
A	302628	0.901	A	V3E002	1.077	A	268199	0.938
B	302628	0.980	B	V3E002	1.029	B	268199	0.871
C	302628	1.163	C	V3E002	0.878	C	268199	0.702
D	302628	1.202	D	V3E002	1.027	D	268199	0.649
			E	V3E002	0.867	E	268199	0.615
			F	301692	0.845	F	269611	0.764
			G	301692	0.746	G	269611	0.759
			H	301692	0.770			
			J	301692	0.895			
			K	302628	0.824			

2.1.3 Step 3: Re-calibrate the Pitman model

Guidelines for estimation of the new parameter values of the GW Pitman model were developed for some catchments in the country (including some Thukela quaternary catchments) through WRC project K5/1498 (Quantification of the groundwater contribution to baseflow). The parameter estimation process was facilitated by the availability of a database of relevant ground water parameters established by Conrad (2005) as part of that project and a DWAF project on Groundwater Resource Availability. Revised parameters for the whole country should be available during 2007 (or early 2008) through the WR2005 (an update of the WR90 database) project funded by the WRC.

If an existing parameter set is available for the revised ground water version of the Pitman model, the re-calibration process is simply a matter of checking that those parameters are appropriate for use with the real-time rainfall data and making any necessary adjustments. If such a parameter set is not available the best approach is to calibrate the model against the most recently generated natural stream flow data using the real-time rainfall data.

In any re-calibration process the point made at the beginning of Section 2.1 of this report should be borne in mind (i.e. that the absolute values of stream flow volume are not that critical, but the frequency, duration and sequencing of wet and dry periods are). The most appropriate test is to ensure that the time series of environmental flows triggered by the revised simulations are similar to those triggered by the original natural hydrology (used at the Reserve determination workshop). Figures 2 to 4 illustrate the results for three Reserve sites within the Thukela basin. 'Original' refers to the workshop natural hydrological data, 'Revised' refers to the results after the first round of the re-calibration exercise, while 'New Revised' refers to a slight revision of the calibration.

Examination of the flow duration curves for the EWR generated with the two different natural flow triggers suggests that there are no major differences in the patterns of requirements. Figure 2 indicates that at site IFR10 there are some dry seasons where the requirements are higher (1976-77, 1982-83, for example) with the revised trigger and some where they are lower (1983-84, for example). There are fewer differences for individual months at IFR14 (Figure 3) and even fewer at IFR15 (Figure 4). This is almost certainly a scale effect and is a consequence of using rainfall data from single gauges as catchment average inputs to the model. These effects will therefore be more evident in headwater areas (IFR10), but as more and more quaternary catchment outflows are added together the effects are smoothed out (e.g. at site IFR15).

A further examination of the GW Pitman parameters for the quaternary catchments upstream of site IFR10 (V20A to D) indicated that anomalous ground water transmissivity values (about 70 m^2 d^{-1}, rather than less than 20 m^2 d^{-1} for other areas) were contained within the Conrad (2005) database. This leads to very rapidly draining ground water and less sustained baseflows than might be expected. When these were adjusted a better correspondence with WR90 low flow patterns resulted. The 'New Revised' EWR estimates in Figure 2 are closer to the original estimates in several years. (see 1975-76 and 1976-77 for example).

The final conclusion reached during the tests on the Thukela basin data is that the re-calibration process has generated time series of 'natural' flows for all the quaternary catchments that can be considered suitable for triggering Reserve requirements. These time series can therefore form the basis upon which future real-time estimates of flow will be compared to the established flow duration curve % points and generate recommendations for managing flows and satisfying Reserve requirements.

It should be noted that the results illustrated in this report are dependant upon the quality and reliability of the rainfall input data for the real-time reporting stations remaining stable into the future. If the quality changes, or if some of the stations experience extensive missing data periods, the quality of the natural flow simulations will suffer accordingly.

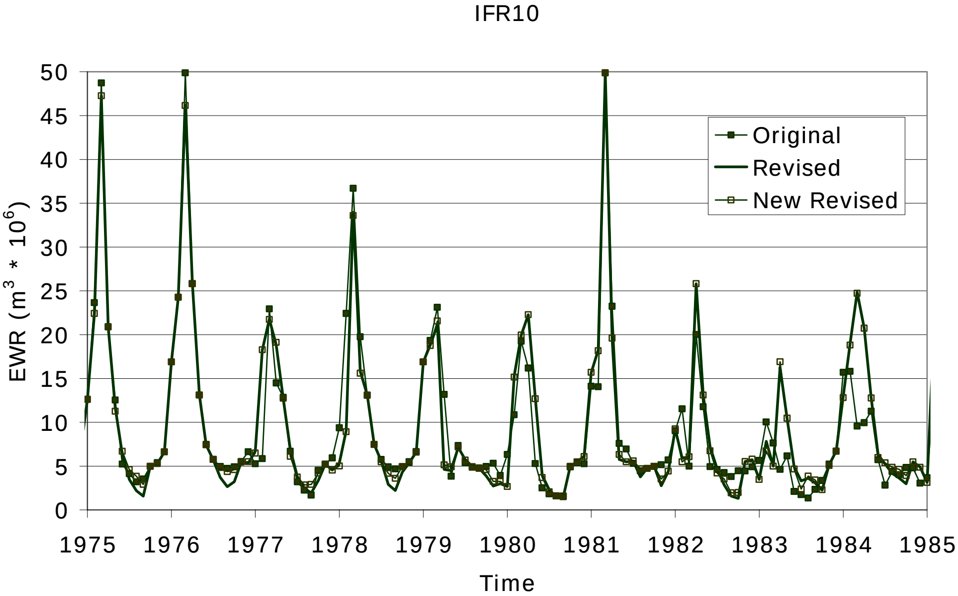


Figure 2 Comparison of ecological water requirements for site IFR10 triggered by the original simulations (used at the workshop) of natural hydrology and the simulations based on the GW Pitman model and reporting raingauge stations

IFR14

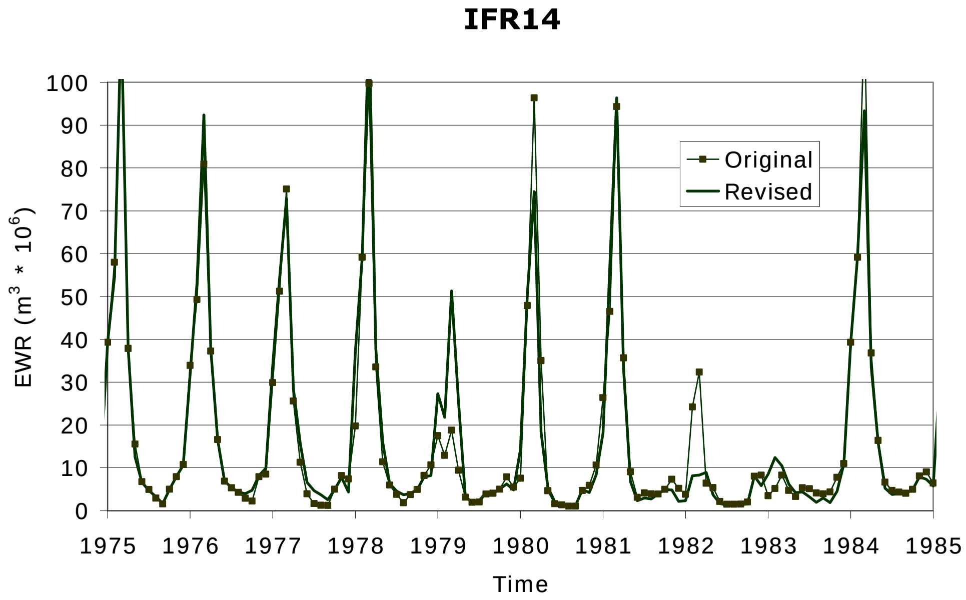


Figure 3 Comparison of ecological water requirements for site IFR14 triggered by the original simulations (used at the workshop) of natural hydrology and the simulations based on the GW Pitman model and reporting raingauge stations

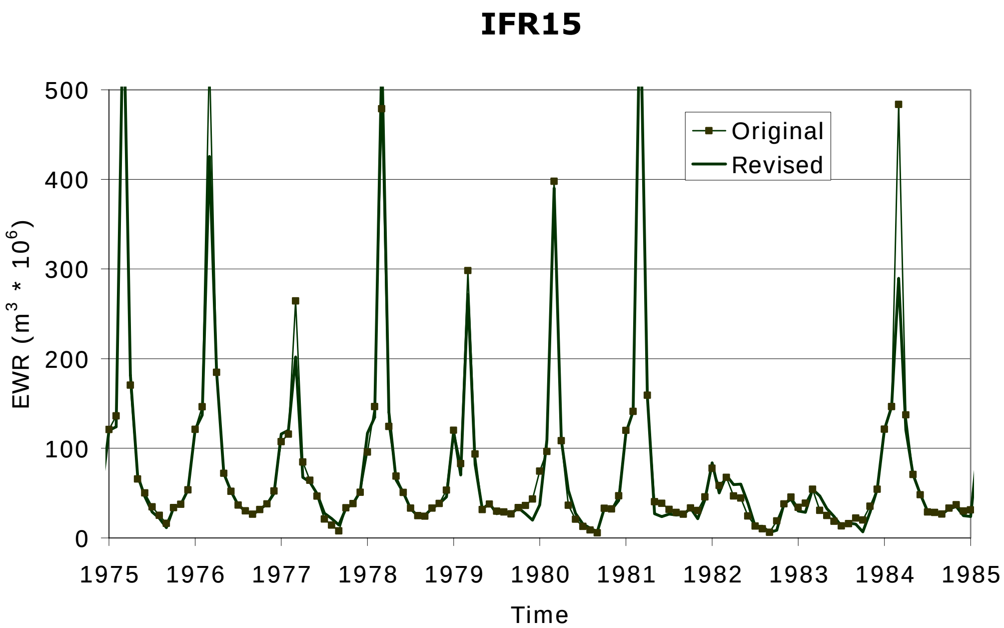


Figure 4 Comparison of ecological water requirements for site IFR15 triggered by the original simulations (used at the workshop) of natural hydrology and the simulations based on the GW Pitman model and reporting raingauge stations

2.2 Establishing the operating rules

The second preparation component involves establishing the various operating rules and the first step in this process is to delineate the Reserve management areas within the total basin being considered. The criteria for grouping of quaternary catchments into Reserve management areas include the existence of a site where a Reserve has been determined (and therefore where Reserve compliance monitoring can take place) and the operational and management infrastructure that exists. The latter will include reservoirs from which releases can be made, but may also account for different types of water use. Perhaps the critical issue to recognise is that a single set of operating rules will apply to each management area. Figure 5 illustrates the management areas that were selected for the Thukela basin. Each one has a Reserve determination site associated with it, some have reservoirs at their upper ends (e.g. V31E to V31J), others have reservoirs controlling part of the flow (e.g. the area above V14E), while others are dominated by run-of-river use (V32A to V33B, V60A to V60F and the lowest area down to V50D).

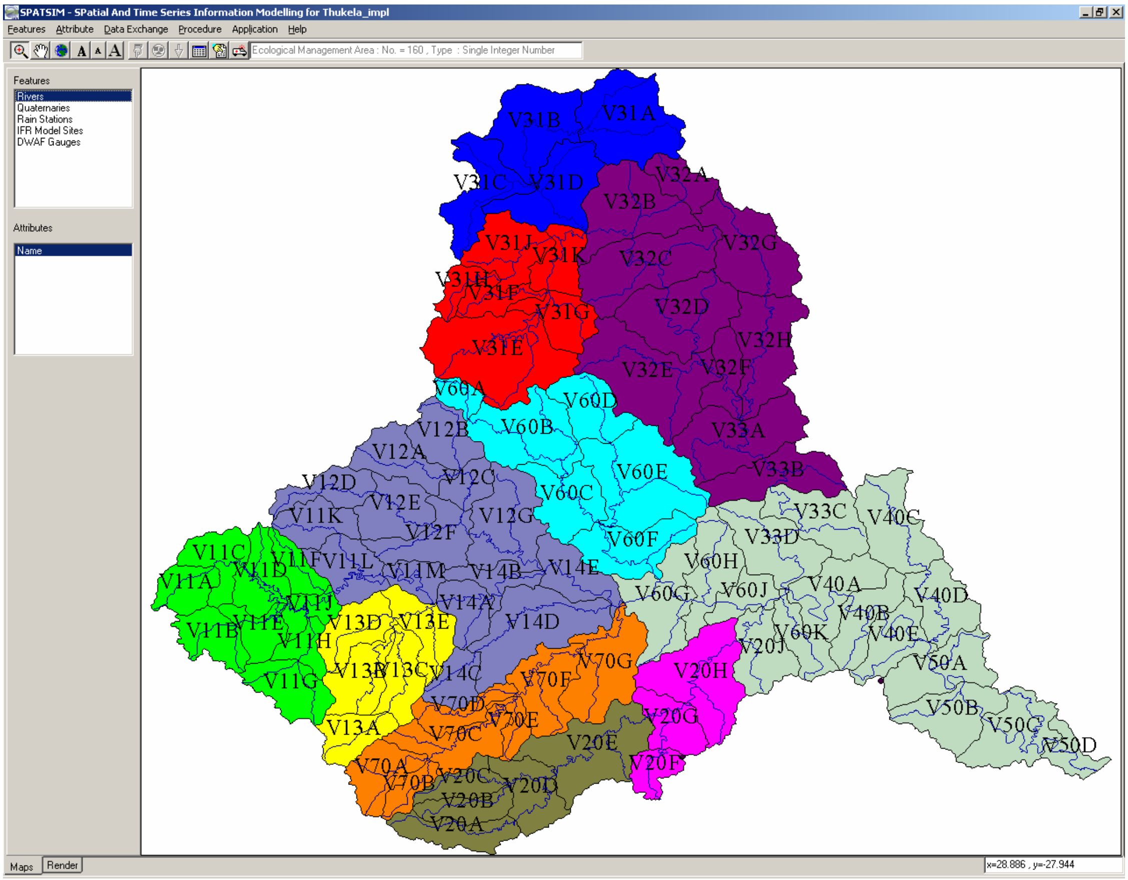


Figure 5 Reserve management areas in the Thukela River basin

For each of these management areas it is necessary to establish five sets of rules, although some are not required if there are no reservoirs from which releases can be made. Establishing these rules requires that a systems yield model be set up and calibrated for the range of water users within the basin. Whether the model is calibrated for existing water use or for some expected future level of water use would be a decision made by the relevant water management authority. The point is that the operating rules that result from the calibration will be those that are used in the real-time management system.

It should be clear that the systems yield model that is used must have the capabilities of including (and quantifying) all the operating rule types that are specified in the following sub-sections.

2.2.1 EWR Targets

These rules are the monthly EWR targets for up to 10 levels of assurance. In practice these could be the flow requirements at the target site (where the flow is expected to be monitored for Reserve compliance), or they could be the releases that are required to achieve the Reserve at the target site, accounting for channel transmission losses and gains (both natural and anthropogenic). The rules are based on the assurance rules determined through the normal Reserve determination process and translated into operational rules.

Where there are no release capabilities, this set of rules would be simply the normal Reserve assurance rules for low flows and would be included in the systems yield model as a high priority demand.

Where releases can be made, the release rules need to be determined using the systems yield model based on the downstream Reserve requirements and any additions (tributary inflows or return flows) or subtractions (run-of-river abstractions or natural losses) of flow. One of the complicating factors is that abstractions between the release point and the Reserve site may be subject to operating rules and curtailments during water shortages (see later rule). The assumption is that the release table would be simplified (using only 4 of the 10 possible assurance levels). An example is provided in Table 9 for Reserve releases from Spioenkop Dam.

2.2.2 Reservoir releases for users

This set of rules represents the normal releases required from the reservoir for up to 5 groups of users for each month of the year (see Table 10 – in this example there is only a single user group). These are the water users who are assumed to be supplied from the dam through managed releases and the water is assumed to be abstracted before the downstream Reserve site. They therefore represent additional releases that would be added to those required for the Reserve. These releases would be subject to curtailments based on the level of water in the reservoir (see sub-section 2.2.3).

Table 9 Releases ($m^3 s^{-1}$) from Spioenkop Dam for the Reserve

FDC % Point	<40%	40-59%	60-89%	>90%
Oct	3.83	3.68	3.26	2.45
Nov	4.66	4.45	3.84	2.69
Dec	5.49	5.22	4.45	3.00
Jan	8.67	8.32	7.28	5.34
Feb	11.21	10.78	9.52	7.13
Mar	9.83	9.46	8.40	6.38
Apr	7.52	7.3	6.66	5.44
May	5.98	5.79	5.22	4.14
Jun	4.67	4.50	4.02	3.12
Jul	3.83	3.69	3.27	2.49
Aug	3.59	3.45	3.03	2.24
Sep	3.59	3.45	3.06	2.31

Table 10 Releases from Spioenkop dam for water users (before any curtailments)

Month	Release ($m^3 s^{-1}$) for user group 1
Oct	1.21
Nov	1.25
Dec	1.22
Jan	1.10
Feb	1.23
Mar	1.15
Apr	1.15
May	1.03
Jun	1.03
Jul	0.96
Aug	0.91
Sep	1.01

2.2.3 Reservoir release rules

These are the curtailment rules that apply to users supplied directly from the dam (the rules discussed in sub-section 2.2.2) and are based on the level of the reservoir. Table 11 illustrates the format of the rules. An allowance is made for 5 rule levels and associated with each is the % of full supply volume and the curtailment percentages for each of the 5 possible user groups. In Table 11 it is assumed that there are two user groups and that the second group is curtailed more severely than the first.

Table 11 Reservoir release rules (applies to water users supplied directly from the dam)

Rule level	% Full Supply	User 1	User 2	User 3	User 4	User 5
		Curtailment as % of normal demand				
1	10	60	0	100	100	100
2	20	70	50	100	100	100
3	40	100	80	100	100	100
4	60	100	100	100	100	100
5	100	100	100	100	100	100

2.2.4 Run-of-river curtailment rules

These rules represent the curtailments for up to 10 assurance levels (the same levels as in the EWR target rules) and 5 user groups. These are the rules that are used to control run-of-river abstractors during periods of limited water availability and would be determined through the system yield model to achieve a long-term water balance within the Reserve management area. An example of this rule table is given in Table 12. The first column represents the rule level and starts at 10 as this represents the severity of the water shortage. The second column represents the % point on the natural flow duration curve that is appropriate to the equivalent rule level. Thus, flows that are less than the flow equaled or exceeded 95% of the time are considered a 'level 10 drought'. The final 5 columns represent the curtailment rules for up to 5 run-of-river user groups. Where there is a reservoir within the Reserve management area, these rules apply to users abstracting water from tributaries that are not affected by the reservoir, as well as any users downstream of the reservoir that are not supplied through controlled releases.

Table 12 Run-of-river user curtailment rules

Rule level	FDC % Point	User 1	User 2	User 3	User 4	User 5
		Curtailment as % of normal demand				
10	95	10	50	100	100	100
9	90	50	80	100	100	100
8	80	80	90	100	100	100
7	70	100	100	100	100	100
6	60	100	100	100	100	100
5	50	100	100	100	100	100
4	40	100	100	100	100	100
3	30	100	100	100	100	100
2	20	100	100	100	100	100
1	0	100	100	100	100	100

2.2.5 *Monthly curtailment factors*

In some situations it is not possible to achieve a satisfactory water balance within a systems yield model without making allowance for seasonal variations in the curtailment rules specified in sub-section 2.2.4 and Table 12. The final set of quantitative operating rules is therefore a table of monthly curtailment factors. These have been added in preference to including a third dimension in Table 12 (i.e. 12 different monthly patterns of curtailment). Table 13 provides an example of a set of correction factors which are applied to all users to convert the 'annual' rules into monthly rules using the following approach:

$\text{Monthly rule}_j = 100 - (100 - \text{Annual rule}) / \text{Correction Factor}_j$ **Equation 1**

Where j is the month and the annual rules for user group 1 illustrated in Table 12 are translated into the monthly rules given in Table 14. This table illustrates that the annual rules remain unchanged for the dry season and early wet season, while no curtailments are deemed necessary in the main part of the wet season. The values in Table 14 would be generated by the systems yield model after calibration and optimization and these would then be translated into the annual rules (Table 12) and the seasonal correction factors (Table 13).

Table 13 An example of seasonal correction factors used to adjust the 'annual' curtailment rules into monthly rules (applies to all users in Table 12)

Assurance level	95%	90%	80%	70%
Oct	1	1	1	1
Nov	1	1	1	1
Dec	4.5	2.5	2	1000
Jan	1000	1000	1000	1000
Feb	1000	1000	1000	1000
March	1000	1000	1000	1000
Apr	9	5	1000	1000
May	4.5	2.5	1000	1000
Jun	1	1	2	1
Jul	1	1	1	1
Aug	1	1	1	1
Sep	1	1	1	1

2.2.6 *Operating rule meta-data*

The real-time operation software developed for SPATSIM includes an option to specify the operating rule meta-data as a memo attribute. This is simply an explanation of the operational system for the specific Reserve management area and may include any information that might explain the origin of the rule data, the basis for the reservoir operation, or any other explanatory information that might be of assistance to the reservoir operator.

Table 14 Application of the correction factors for user group 1 in Table 12

Assurance level	95%	90%	80%	70%
Oct	10	50	80	100
Nov	10	50	80	100
Dec	80	80	90	100
Jan	100	100	100	100
Feb	100	100	100	100
March	100	100	100	100
Apr	90	90	100	100
May	80	80	100	100
Jun	10	50	90	100
Jul	10	50	70	100
Aug	10	50	70	100
Sep	10	50	70	100

2.2.7 The systems yield model and other considerations

Clearly the choice of systems yield model will largely depend upon the capabilities of the model and whether or not it is able to account for (and therefore quantify) the various rules referred to above. The model described by Mallory (2005) has been designed specifically to account for all these rules. In other cases it may be necessary to interpret the model outputs in terms of the information required for the rules, or to adapt the operating rule structure of the model to match the requirements of the real-time model.

Many of the operating rules referred to above relate to a maximum of 5 user groups. This feature has been included to allow for quite complex water supply systems where there are a range of different water use sectors that require separate operating rules. In many cases, within a single Reserve management area, there will be only one or two water use sectors. It is not expected that there will ever be more than 5 and should this appear to be the case, it is probably necessary to sub-divide the original Reserve management area.

Deciding on the different operating rules (i.e. curtailment levels) for different user groups will never be a simple task and will normally involve inputs from the users themselves. There do not seem to be appropriate methods that are readily available to resolve the socio-economic dynamics of the impacts of various curtailment scenarios. Hughes and Mallory (2007) have discussed this issue and propose an approach that might be useful if it can be combined with social and economic impact models.

3. SETTING UP A HIGH FLOW MANAGEMENT SYSTEM

The high-flow component of the Reserve consists of a number of events that are defined by the required peak and duration (the shape of the hydrograph is assumed to be similar to a high flow of a similar peak that would occur under natural conditions). They are typically specified as being required during certain months of the year, although the exact timing in any one year is assumed to reflect the natural occurrence of such events. Similarly, the high flow requirements that are defined are for 'maintenance' years and it is accepted that in wetter years larger (or more) events will occur, while in drier years the events may be curtailed (fewer or lower peaks).

It has been long recognized that the management of high flows for Reserve purposes is only possible where there are reservoirs with sufficient storage and release capabilities to control flows over the range of the requirements. This means that in some systems, some of the high flow requirements can be managed, while others cannot.

There are four main issues that need to be considered in the interpretation of the high flow results of a Reserve determination and in establishing the high flow operating rules.

Attenuation and losses: The first critical issue is that the water released from the dam will not be the same as the Reserve requirement downstream. The release pulse will be subject to attenuation of the peak as well as losses to satisfy pool storage, bank storage and evaporation. The exact degree of attenuation and the amounts of water that will be lost will be highly site specific and not a simple task to estimate. While, clearly the greater the distance between the release point and the Reserve monitoring site, the greater will be the losses and attenuation. These will also be greater when the difference between the existing low flows in the river and the high flow peak is greater. Within semi-arid systems, a high flow release may be made into a previously dry channel (i.e. no low flows). In such cases, the losses and the delays in water reaching the Reserve site could be very high due to satisfying pool storage and because of seepage into a dry river bed. A test release of about 2.5 m^3 s^{-1} in the Nahoon River (with a dry channel before the release) suggested that the delay in the arrival of the release pulse was about 1.8 h for every 1km channel distance. The degree of peak attenuation was relatively small, but this was a long and continuous release. The amount of attenuation in an event based release would have been substantially greater.

Tributary inflows: From a water resource management perspective, any Reserve requirement should be met with the minimum amount of released water. The previous section already indicates that more water than is required at the site will have to be released. However, the amount of release water could be reduced if there are tributary inflows between the release site and the Reserve site and if the release can be timed to match those inflows.

Release timing: The stated objective of any real-time Reserve operation is to achieve a modified flow regime that reflects natural flow conditions. With respect to low flows, this effectively means preserving seasonality and some degree of flow variability. In terms of high flows, it is ecologically important that they occur at specific times in relation to the life-cycles of the biota. It may be important in some river systems that the high flows in the main channel coincide with high flows in the tributaries. If this does not occur there may be ecological consequences associated with the lack of connectivity of important habitats. In that respect, the ecological and water management objectives would be the same. Less water would need to be released if the release coincided with tributary inflows. However, achieving that objective will never be a simple task and will be even harder when the natural hydrological response time of the system is quite short (small and steep catchments). The key to this issue is therefore being able to identify real-time trigger information that is accessible to the water resource manager and can be used to reliably identify the appropriate time to make releases.

Safety: A final consideration, particularly relevant to large releases, is the necessity to provide riparian river users with adequate warning of a high-flow release. This may include members of the public who make use of the river for recreation or other purposes, as well as farmers whose stock may use the river or banks for drinking and grazing. While this issue is not specifically addressed in this report, it is essential that it is considered as part of the operational management of high flows.

3.1 Accounting for attenuation and losses

The accurate estimation of hydrograph attenuation and losses depends to large degree on the amount of information that is available to define the channel cross-section, longitudinal slope and hydraulic roughness characteristics of the reach between the release point and the Reserve site. The effects of lateral inflows (flow from major tributaries, as well as distributed inflows from ground water seepage or other sources) must also be accounted for. Given that detailed information is available, there are a number of hydraulic routing software packages that could be used to define a release hydrograph that would be required to achieve a specific Reserve objective downstream. While this modeling exercise only has to be done as part of the design phase of the project (assuming that the channel characteristics will remain largely stable), the costs involved in collecting such data are substantial. Costs could be reduced by surveying a few sample cross-sections and assuming similar channel characteristics over sub-reaches within the total reach. The number of samples would depend upon the degree of variability of channel types within the total reach. The use of this type of hydraulic model is the recommended approach, but it is recognized that it would normally require resources that would not typically be available for all Reserves that need to be implemented.

A somewhat simpler approach would be to use a model based on hydrologic routing and the discharge-storage relationship. For example, the Muskingum model is simple to implement in a spreadsheet and has been demonstrated to be a useful approximation in a wide range of natural river systems. The problem lies in determining the values of the storage (X) and routing (K) coefficients that are applicable to the specific reach. If the reservoir that will be releasing the Reserve requirements is already constructed, the most straightforward approach is to use a set of trial releases to calibrate the coefficients of the model. While the coefficients are likely to vary with the size of the event, it should be possible to make an acceptable approximation of the value of the coefficients with three trial releases covering moderate sized events. This approach assumes that there will be a facility to gauge the release at the Reserve site. This should not be a serious restriction, as it is assumed that the ability to gauge flows at the Reserve site will be required for the monitoring component of Reserve implementation.

In semi-arid channels, or where releases are made into dry channels, it may be necessary to account for initial losses. This can probably be achieved by an estimate of the average channel width, average pool length and depth and frequency of pools. An assessment based on the interpretation of aerial photographs may be adequate to obtain a rough estimate which may be sufficient to start with. Adjustments can be made after experience of several releases.

In situations where more than one gauging station already exists within the reach (or in a similar reach within the same channel system) a pre-implementation assessment could be made using the available records. It would be necessary to obtain the primary (breakpoint) data, as mean daily flows will not be sufficient to estimate the coefficients of the routing equation.

Figures 6 and 7 provide two examples of how the simple Muskingum storage-routing equation could be used to design release strategies for defined downstream hydrographs. The assumption is made that the equation coefficients have been pre-calibrated using trial releases. Figure 6 is based on coefficients [X=0.2, K=10 h], initial losses assumed to be 100 $*10^3$ m^3 and a downstream target peak of 5 m^3 s^{-1}, with a total event duration of 3 days. The Desktop Reserve model suggests that the volume required would be 778 $*10^3$ m^3, while the actual volume released (including the allowance for losses) is less than 520 $*10^3$ m^3. However, it should be noted that the peak value used in the Desktop model is actually the mean daily flow peak, while the peak indicated in Figure 6 is the instantaneous peak. The maximum release required is 7 5 m^3 s^{-1}.

Figure 7 represents the situation based on coefficients [X=0.2, K=8 h], no initial losses, an assumed baseflow of 0.2 m^3 s^{-1} and a downstream target peak of 15 m^3 s^{-1}, with a total event duration of 3 days. The Desktop Reserve model suggests a required volume of 1555 $*10^3$ m^3 for a mean daily flow peak of 10 m^3 s^{-1}, while the actual released volume is 1382 $*10^3$ m^3.

In both cases the pattern of design releases is stepped (with a minimum step duration of 3 hours) to allow for operational management and to prevent too-rapid increases of flow anywhere within the downstream reach. Clearly a different pattern of releases could be defined to achieve a similar downstream objective and the final design may depend upon other management constraints. The main point to be illustrated by the two diagrams is that, assuming representative values for the coefficients (X and K) can be determined for a range of high flow peak values (it is assumed that K will decrease as the peak increases), this simple approach can be used to design release strategies. In both cases any incremental flows within the reach have been ignored.

The output from these pre-implementation assessments would be the peak releases required to achieve downstream high flow objectives that have already been quantified through the Reserve determination process. This information can be used directly in the real-time high flow release management software that has been developed as part of the project.

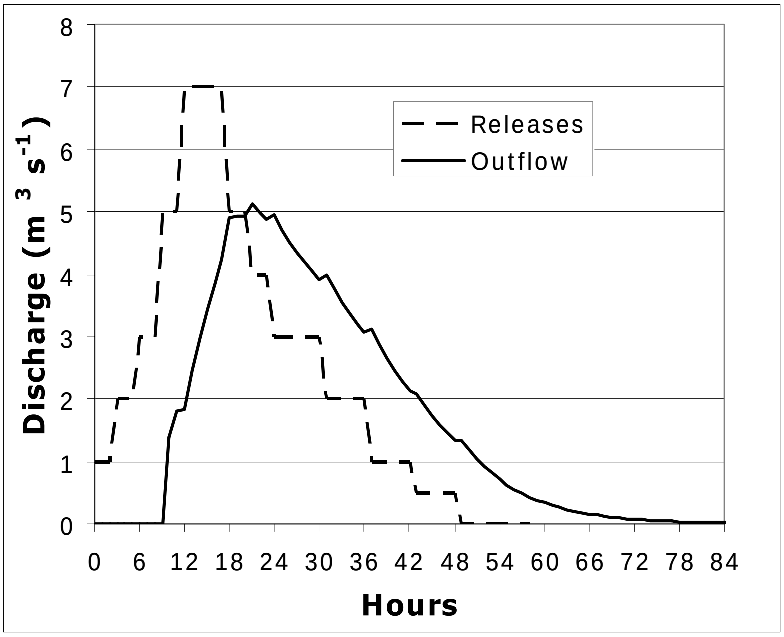


Figure 6 Example release and resulting downstream hydrograph (peak of 5 $m^3 s^{-1}$ with a dry channel and assumed 100 *10^3 m^3 initial losses)

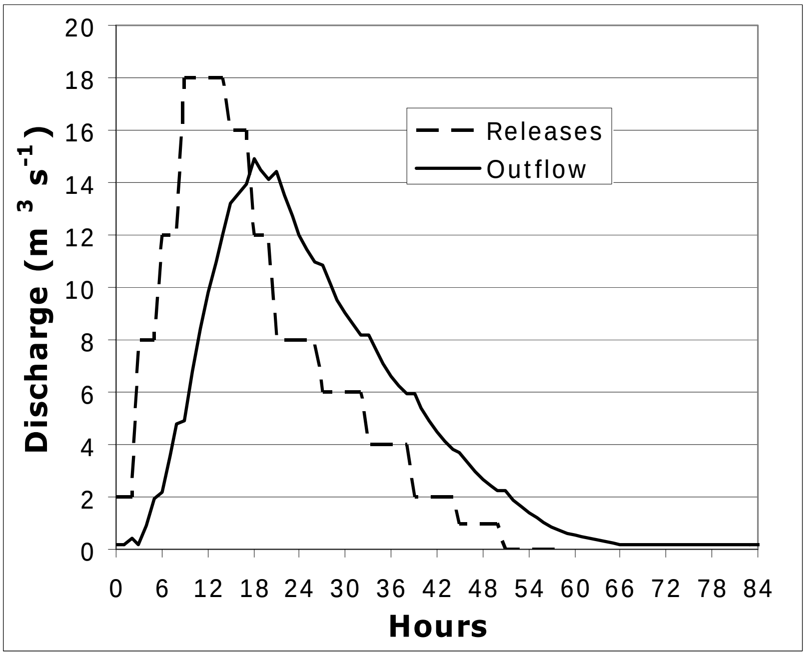


Figure 7 Example release and resulting downstream hydrograph (peak of 15 $m^3 s^{-1}$ with a baseflow of 0.2 * $m^3 s^{-1}$)

3.2 Accounting for tributary inflows

If the Reserve site (i.e. the river cross-section or reach where the Reserve objective is to be met) is distant from the reservoir release site, it is possible that tributary inflows could contribute to satisfying the Reserve if inflow events occur at the same time as releases are made into the main channel. Releases from the reservoir could then be substantially reduced. There are two main issues that would need to be resolved:

- The first is whether, under natural conditions, it is likely that tributary events occur simultaneously with events in the main channel.
- The second is whether information can be made available to allow managed releases to coincide with tributary events.

An analysis program has been developed as part of the SPATSIM package to be able to estimate the level of contribution that tributaries have made (or will make) under certain conditions. The main input to the program is a set of daily flow time series (that can be obtained from stream flow gauges or from a suitable simulation model), one for the Reserve site and one for each of up to 10 representative tributaries. It is also necessary to know the MAR at the reservoir site (or immediately above all the tributaries being considered). This analysis is typically based on mean daily flow data (not instantaneous flood peaks) and therefore is unlikely to be valid for small catchments.

While the analysis will give more accurate results if all the tributaries are accounted for in the input time series, the tributary inflows at the times of identified downstream peaks are scaled by the assumed incremental mean annual runoff relative to the mean annual runoff of the input tributary inflows. Thus, unmeasured tributaries can be accounted for in a simplified manner.

The results are displayed as a Box and Whisker plot of % tributary contributions for a range of flood peak groups at the Reserve site (see Figure 8 for an example of the results display using the main stem of the Thukela River below Spioenkop Dam and down to Reserve site IFR9). The example illustrates that for most of the different size peak groups, the median contribution is of the order of 50% (under current conditions), while it can be as low as 35% and frequently is as high as 75%. Clearly, if the future development conditions in the tributaries change then the expected contributions could change as well. The interpretation of these results for a downstream objective of 150 $m^3 s^{-1}$ is that, if a release with a peak flow of 75 $m^3 s^{-1}$ is made, there is:

- A 95% probability that the resulting downstream peak will be > 105 $m^3 s^{-1}$.
- A 75% probability that the resulting downstream peak will be > 130 $m^3 s^{-1}$.
- A 50% probability that the resulting downstream peak will be > 150 $m^3 s^{-1}$.
- A 25% probability that the resulting downstream peak will be > 180 $m^3 s^{-1}$.
- A 5% probability that the resulting downstream peak will be > 270 $m^3 s^{-1}$.

Given that the high flow requirements of a Reserve determination are always specified as a range of flood peaks to achieve a defined ecological objective, this result would be acceptable from a Reserve perspective.

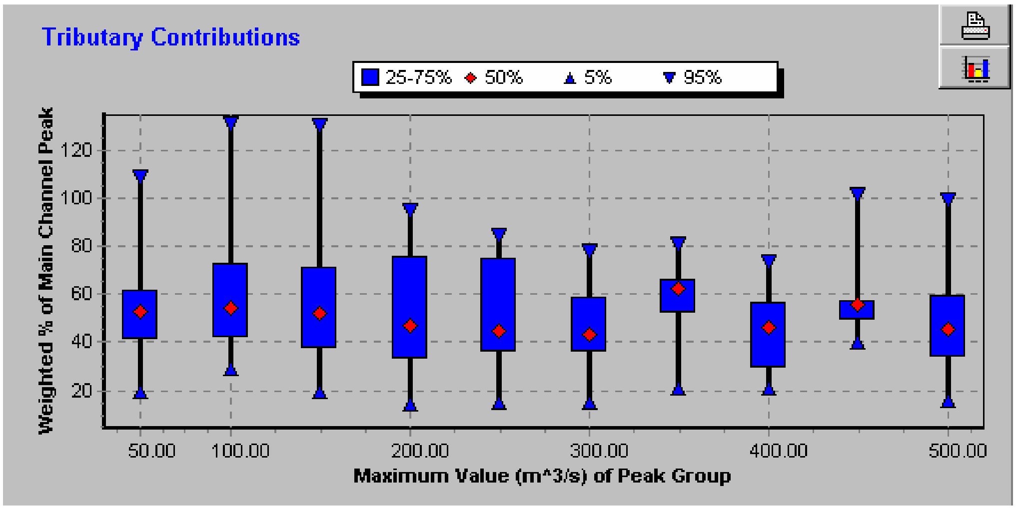


Figure 8 Results output from the Tributary Inflow Analysis model

3.3 Real-time triggers for high flow releases

The most difficult issue to resolve is the real-time triggering of the releases. Clearly, if the timing is not appropriate, the tributary inflow analysis results using historical data will not be relevant as the releases from the dam will not match the natural flow events in the tributaries. Having noted that problem, it is important to recognize that no method that attempts to 'look into the future' will ever be perfect and it is unlikely that even releases made on the basis of a sophisticated forecast will always be correct. The results of setting up the low flow management system for the Thukela basin suggest that obtaining real-time data (either rainfall or flow) that can be used to trigger releases is currently not an easy task. While this is expected to improve in the future when the importance of such data is more widely recognized, it is difficult to predict how long it will be before real-time data will be obtainable with the required accuracy and urgency.

The requirements for real-time data to manage low flows are far less stringent than those for managing high flow releases. This is mainly because changes in low flow releases are slower and it does not matter too much if they are somewhat delayed (10 to 20 days) with respect to natural low flow responses. There are a number of options that are available for triggering high flow releases, all of which suffer from similar problems:

- Can the real-time data be obtained in time to make appropriate management decisions? From a high flow point of view this means obtaining flow or rainfall data with a delay of less than 1 day.
- Are the data appropriate for determining high flow releases? This means that the data must have some relationship with natural high flow occurrences in the channel reach under consideration.
- Can the real-time data be extrapolated into the future to determine whether a release is appropriate or not? This is the forecasting component of the method.

Deliverable F investigated the use of the so-called Daily IFR model of Hughes et al. (1997) which uses observed flow data as a trigger. The assumption is that the observed flow data would be collected from a gauge at the outlet of a catchment with similar natural hydrological response characteristics as the catchment above the release point. It is further assumed that the gauged flow data represents natural conditions. There are situations where such a gauge could be identified, but there are also many situations where it would not be possible to identify such a gauge. Deliverable F also referred to a relatively simple approach based on thresholds of daily rainfall measured during the previous 24 hours. The results were not very encouraging and further attempts to improve this simple approach did not achieve a great deal.

During the preparation for Deliverable G it became apparent that a very simple approach is unlikely to succeed, but that a very complex approach would be inappropriate as it would be unlikely to overcome many of the uncertainties associated with the whole method. It was also recognized that the application of the integrated Reserve implementation approach would be made easier if the data requirements for the high flow component were as similar as possible as for the low flow component. The implication is that the high flow component should also be based on real-time rainfall data. Later sections of this report provide complete guidance for the use of an approach that has been developed which relies quite heavily on the so-called patching model of Hughes and Smakhtin (1996) and more specifically on the application of a similar approach using rainfall data to estimate time series variations in flow data (Smakhtin, 2000).

3.3.1 The rainfall patching model

The basis of the so-called Patching model of Hughes and Smakhtin (1996) is to use calendar month flow duration curves to transform one or more time series of flow data (the source sites) into a time series of flow for a different catchment (the destination site – typically ungauged). The assumption is that there would be some method of deriving the flow duration curve characteristics for the destination site

The rainfall patching model was a later development that simply uses smoothed rainfall time series (CPI – current precipitation index) as the source data instead of flow data. The algorithm for estimating the time series of CPI values from raw daily rainfall data (P) uses a single parameter (RC), referred to as the recession coefficient:

$$CPI_i = CPI_{i-1} * RC + P_i$$

Where the suffix i refers to the current day.

Several rainfall stations can be used together and their effect on the final combined CPI controlled by weights. In all other respects the model is the same as when using flow data as the source data, in that the CPI values are transformed into flow estimates through their calendar month duration curves and the estimated flow duration curve of the destination site.

The use of this approach was assessed using flow data observed at V6H002 (despite the problems associated with this gauging station) together with daily rainfall data from three of the real-time gauges used in the low flow component of the study (Bergville, Cathedral Peak and Rosleigh). The important issue to assess is how well the rises and falls in the observed flow can be predicted by the rises and falls in the generated CPI index, as it is the latter which have the potential to be used to trigger releases. Overall, the predictions are not very good, while in some years they are better than others. A large part of the problem seems to lie with the high degree of spatial variability of rainfall in the Drakensberg catchment area of the Thukela that is not adequately reflected by the available rainfall stations.

Despite these problems it was decided to proceed with the design of software that would be linked to the SPATSIM system and the software already developed to manage the low flows in the Thukela River system.

3.3.2 A model for release triggers

The details of how to use the model are covered in a later section of this report, while this section outlines the background to the development of the model. The developed model was required to include the following features:

- An interface with SPATSIM that allows the relevant input data to be accessed. The relevant input data includes the real-time raingauges to be used to generate the weighted CPI index, the rainfall patching model parameters (recession coefficient and weight for each raingauge), the high flow release details (peak, duration, month(s) of release, hourly release pattern, expected relative contribution of downstream tributaries during the release, etc.) and the daily rainfall data.
- Note that for the high flow releases the daily rainfall data needs to be updated on a daily basis, while for the low flows a 10-day cycle was considered sufficient. This means that the real-time rainfall input program (see Section 4) would need to be applied a lot more frequently during wet periods when it might be expected that a high flow release is required. It also means that a more efficient (and immediate) system for collecting the rainfall data than currently exists would need to be established.
- A procedure for generating the weighted CPI data using all the historical rainfall data, as well as a procedure for determining the historical events that would have been released. The latter requires a 'rule base' that uses the CPI data to determine when to make a release and how big the release should be.
- A procedure to make a future 'forecast' based on current information to determine if a release should be made in the near future. This procedure should be applicable to either the current day (i.e. the last day of available rainfall data) or any previous day so that a 'forecast' can be compared with what actually happened historically. The basis for the forecast would be daily rainfall data which would be converted to CPI values. The 'rule base' referred to in the previous bullet point would then be used to determine if a release is required.
- A support system to guide users in the process of making a decision about whether to make a release or not. This is essentially the real-time version of the same procedure that will be used to generate a time series of historical release patterns (third bullet point above), but will need to include a process for storing the information about actual releases that were made. This means that it has to account for any 'user intervention' in the decision support process that affects whether a recommended release is made or not, as well as the size of the release. The importance of this is related to the fact that a season of releases must be seen as a group and not as independent individual releases. Therefore some of the releases made (or not made) early in a season may affect releases later in the season.

- Procedures to store any generated information (CPI values, releases, etc.) for further analysis or future use.

Table 15 illustrates how the high flow requirements have been defined for the model. Each row in the table represents a high flow as defined in the Reserve determination process. The second column identifies the flood class, while the third and fourth columns the range of peak flow that is associated with the high flow event required downstream. It is assumed that the majority of the events that should be released would fall within this range. The fifth column defines the duration of the event (and therefore the shape of the release hydrograph). The sixth column ('Scale') refers to the release that will be made relative to the event peak required downstream and would be quantified on the basis of expected attenuation effects as well as tributary contributions. The 'Month' column specifies the ideal month for the release to be made, while the final column indicates whether an event can be carried over into future months if not triggered in the ideal month. For example, if event numbers 1 to 6 are not triggered in the specified months they would be lost. However, if event number 15 is not triggered in December, it can be carried over and triggered in January to March (a maximum of 3 months carry over). The information requirements listed in Table 15 are fully compatible with the type of information generated by a Reserve determination.

Table 15 Example of high flow input requirements for the model (mdf refers to peak mean daily flow in $m^3 s^{-1}$)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]	[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

3.3.3 The release 'Rule Base'

As already indicated the 'rule base' for releases uses the CPI values generated from the daily rainfall data. However, instead of using this information directly (which would be subject to problems of scale), the model uses the % points of the CPI calendar month frequency curves. The historical CPI data are therefore first ranked and converted into frequency of exceedence tables for each calendar month of the year. Any CPI value can then be converted into a frequency of exceedence value. These values are then inverted (100 – value) so that high CPI values generate high % points.

The release rules are then based on the rate of rise in the inverted % points between the current day and the 'forecast' next day, as well as the inverted % point 'forecast' for the next day. In historical mode (i.e. generating releases for the complete historical period), the 'forecast' information is simply the next days calculated value of the inverted % point. In real-time mode the 'forecast' of the next day's rainfall is used to generate the CPI value and therefore the inverted % point. The rate of rise is used to determine whether any release is appropriate (a rate of rise of greater than 20% is currently required), while higher values of the inverted % point for the 'forecast' day are required for progressively higher classes of events. Figure 9 illustrates one possible scheme of rules based on a maximum of 6 classes (or categories) of flood event. Referring back to Table 15, a number 15 event (peak of 140 to 220 $m^3 s^{-1}$) would require a 'forecast' inverted % point of 90% before a release could be triggered. If the historical record is about 30 years in length (approximately 900 days per calendar month), this would equate to situations that occurred on average 3 days per year in the appropriate month ((100 – 90) * 900 / (30 * 100)). The implication is that such an event would not be triggered in years with lower peak values of the CPI index.

The use of the inverted % point solves potential problems of differences in typical sizes of flood events and CPI values between different calendar months and allows a simple generic rule base to be used for all months.

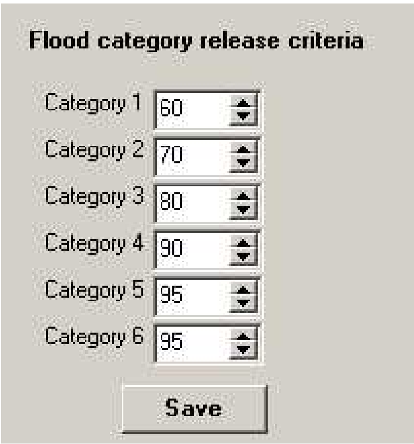


Figure 9 Release rules based on the inverted % point for the 'forecast' day

A peak factor is calculated to determine where in the range of the two defined peaks (Peak 1 and Peak 2 in Table 15) the released peak should be:

Peak Factor = 0.6 * (ROR – 20)/(100-20) + 0.4 * (Day2 – CRIT)/(100 – CRIT)

Where: ROR is the rate of rise (current day to forecast day) of the inverted % point,
Day2 is the inverted % point on the forecast day,
And CRIT is the appropriate release criteria (threshold) from Figure 9.

If an event is not triggered in a specific month, but carried over to the next month then the criteria (CRIT) is relaxed by 5% for every month that the event is carried over (i.e. if a class or category 4 event is carried over 1 month then the inverted % point criterion becomes 85 instead of 90 – see Figure 9). The rainfall forecast is based on the patterns of rainfall that occurred during the 10 days prior to the current day. This sequence of daily rainfalls is compared to all possible 10 day rainfall sequences within the available historical records for the gauge and the best possible match is found (based on an unbiased statistical measure). The 'forecast' for the next 10 days is then the set of daily rainfalls that follow on from the period identified as the best fit.

3.3.4 Data preparation for the high flow operational system

The main data preparation for the high flow management system is to choose the rainfall stations that will be used to generate the CPI signals from those already selected as real-time reporting stations and to calibrate the recession coefficient and the stations weights. The selection of stations will be largely based on the same criteria as those used for selecting the stations to use for input to the real-time Pitman model. However, additional considerations may be related to the reliability with which the data can be provided with a short lead time (essentially the daily rainfall data for the previous day need to be obtained by about 8h00 on the day that a release decision may be made).

The rainfall patching model is an established model within the SPATSIM framework and the calibration of the rainfall station weighting factors as well as the recession constant can be undertaken using that version of the model. Alternatively, the real-time high flow management software (see Section 6) allows the user to generate and save to SPATSIM an historical record of CPI values and triggered high flow releases which can be compared with a gauged stream flow record to assess the calibration parameters.

3.3.5 An assessment of the 'forecast' approach using the Thukela data

It must be clearly recognized that the 'forecast' method used is extremely simple and unlikely to be all that reliable in most cases. It has been included in the absence of any viable and readily obtainable alternative. A rough test has been carried out by generating 60 'forecasts' during the period 2003 to 2006 (approximately 2 for each main high flow event month). The 'forecasts' were categorized into those which were very good (a very close approximation to the 'real' pattern of CPI values), good (generally the same pattern), average (the same pattern part of the time, but not very similar at other times during the 10 days), poor (too many days in the period when the direction of change of CPI values was quite different, i.e. forecast decreases in the CPI values when there were increases) and bad (no correspondence between the 'forecast' and the real values). Table 16 lists the percentage of the samples falling into each category, while Figure 10 provides some graphical examples of the range of results.

Table 16 Percentage 'hits' falling into different 'forecast' quality categories

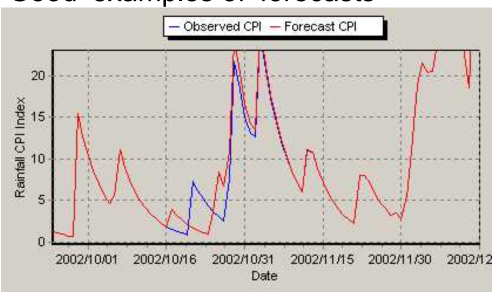
Category	Very good	Good	Average	Poor	Bad
% hits	25	25	20	20	10

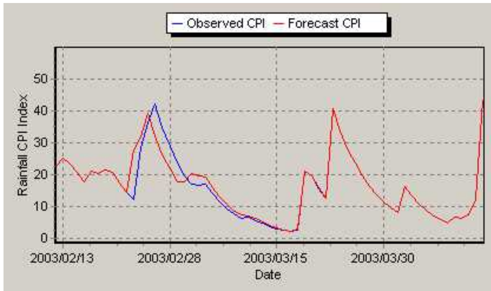
It is interesting to note that even when some of the initial parts of the 'forecast' are not very good, later in the forecast period the predicted CPI improves relative to the real situation. This implies that the use of the forecasts for warning of an impending release might also be useful.

3.3.6 *Evaluation of the use of the CPI to trigger event releases*

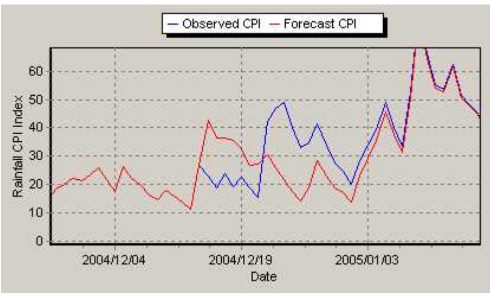
The value of the CPI approach to triggering event releases depends upon the daily rainfall data used, the parameters of the model as well as the suitability of the model itself. Smakhtin (2000) demonstrated that the model can be used under a variety of situations to simulate observed flow data. However, the results from an assessment based on the Reserve management area above V14A suggest that false triggers are generated quite frequently. This appears to be largely caused by the use of the three raingauges (Roseleigh, Bergville and Cathedral Peak) that are available in the catchment area above quaternary catchment V14A. While they may be adequate to generate simulations of monthly flow variability, they appear to be less useful for generating adequately reliable signals of short-term hydrological response that are required for triggering high flow releases. This is a problem that is specific to the Thukela catchment where the headwaters are located in a region of high rainfall variability and where there are very few rainfall observation stations that can provide information in real-time.

‘Good’ examples of ‘forecasts’

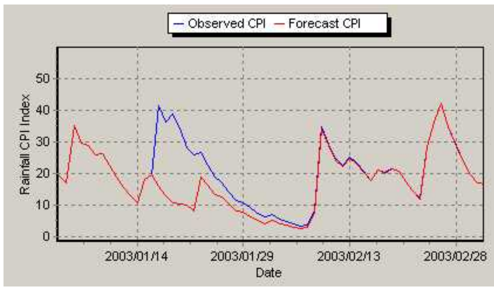




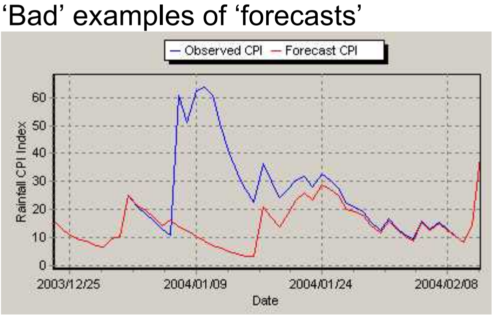
‘Average’ example of ‘forecast’



‘Poor’ example of ‘forecast’



‘Bad’ examples of ‘forecasts’



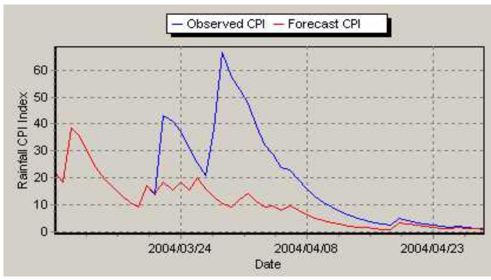


Figure 10 Some graphical examples of rainfall ‘forecasts’ translated into weighted CPI time series and compared with CPI values based on real rainfall data (the results are based on the use of three raingauge stations)

Table 17 lists the number of events (see Table 15 for the event definitions) that were triggered using the criteria set given in Figure 9 (Set 1) as well as an alternative set using 50% for category (class) 1 events and 60% for category 2 events. The length of the record is 46 years (there are 47 October, November and December months). It is clear that a reduction in the trigger criteria generates more events, but it is also clear that many of the specified events are not triggered and that the larger events take precedence over the smaller ones. The latter is a consequence of the model algorithm that searches for a suitable event from the highest class (category) downwards. Part of the problem may also lie in the fact that there are frequently not enough days in a month to be able to trigger all the events without overlap. Criteria set 1 generates an average of 8.4 events per year, while this increases to 9.5 for criteria set 2.

Table 17 Number of triggered events for two different release criteria sets

			Criteria Set 1		Criteria Set 2	
Event Number	Month	Event Class	No. of events	Total in class	No. of events	Total in class
1	Feb	1	19		10	
2	Mar	1	24		28	
3	Sep	1	30		35	
4	Oct	1	36		42	
5	Nov	1	14		20	
6	Dec	1	18	141	20	155
7	Feb	2	9		24	
8	Mar	2	13		24	
9	Nov	2	26		33	
10	Dec + 1	2	34	82	42	123
11	Jan + 1	3	22		21	
12	Mar + 1	3	29		29	
13	Nov	3	26		24	
14	Dec	3	17	94	17	91
15	Dec + 3	4	34	34	35	35
16	Dec + 3	5	34	34	33	33

4. THE LOW FLOW MANAGEMENT SYSTEM – RAINFALL DATA ENTRY AND PROCESSING

This part of the report serves as an explanation of the software that has been developed as well as a user manual for the software. The program can be launched from SPATSIM by selecting 'Application', 'Run Process', 'Directly' from the main menu and then selecting 'Daily Rainfall Capture Process'. It can also be run without launching the SPATSIM program first. The main screen for the software, using the Thukela example, is illustrated in Figure 11. There are two main steps in the process; the first to update the station daily rainfall data and the second to prepare the monthly rainfall data for input to the real-time rainfall runoff model.

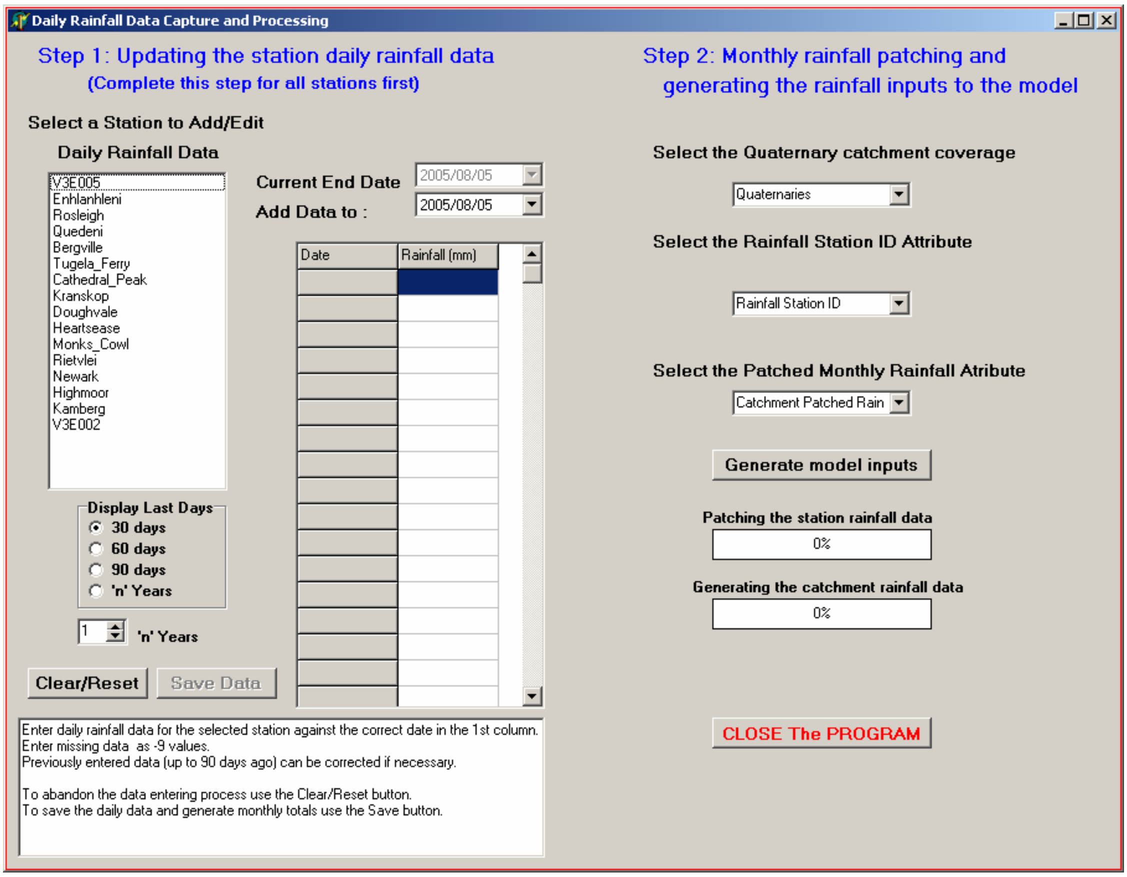


Figure 11 Main screen of the daily rainfall capture process software

4.1 Step 1: Updating the station daily rainfall data

Figure 11 illustrates that a complete list of all the rainfall stations is provided on the left hand side of the screen. The assumption is that updated rainfall data will be provided from the source (SAWS or DWAF) over a cycle of 7 to 10 days (or more frequently during the wet season for those stations that are to be used for the real-time high flow management system).

The selection box below the list of stations allows the user the option of displaying different lengths of past data for a specific station. This can be useful if previously supplied data has been updated and the daily rainfall data need to be corrected.

4.1.1 Step 1.1: Select the station and review existing data

First ensure that the 'Display Last Days' selection is set to the required past period length and then select a specific rainfall station by double clicking on the station name in the list. The archived data will be displayed in the grid to the right for all the data up to the last recorded day. Use the slide bars to navigate within the data, or simply click on a grid cell and use the up and down, or page up and page down arrow keys.

4.1.2 Step 1.2: Add new data or edit existing data

To edit existing data simply over-type the existing value in the grid with the new value. To add data for new days, click on the 'Add Data to:' date box and select the date that you wish to add data to. Note that a maximum of 30 days beyond the current end date is allowed for. Once a new date has been added, additional rows will be entered in the grid with the correct date shown and the second column populated with zero rainfall values. These values are left justified to assist with identification. The new rainfall data can then be added by over-typing the zeros.

The changes made to the data can be rejected by clicking on the 'Clear/Reset' button, or saved to the SPATSIM database by clicking on the 'Save' button. If the latter option is chosen a monthly rainfall summary is generated that compares the old (before new data entry) with the new values. The user is requested to confirm that the data are correct. If large rainfall values are found within the data to be saved the user is also asked to confirm that these are correct.

Note that it is not unusual for rainfall observers to accumulate rainfall values over a few days (if they have been away or simply did not read the gauge). It is normal practice to note this on the recording form. These can be entered into the grid as accumulated values and this will make very little difference to the monthly model used for low flows. However, the user should be aware of the implications if the accumulated rainfall is quite large and crosses a month boundary, or if the station is being used for the high flow release triggers.

Missing data are entered as -9 values and the software is designed to still function even with quite a lot of missing data (albeit with lower accuracy). However, if there are substantial amounts of missing data across several stations it is possible that the program will not be able to find suitable monthly rainfall for a group of quaternary catchments. In such cases a warning will be given and it may be necessary to perform a small amount of manual missing data infilling.

It should be recognized that a few days of missing data at a critical station will result in a complete month of missing data. In some cases the rainfall during the missing data period may have been minimal, while other parts of the month may have experienced significant rainfall. Excluding the whole month may have a greater adverse impact on the runoff simulations than either assuming zero rainfall for the missing days or estimating (or even guessing) the rainfall on these days. The operator should be instructed to use his/her discretion in situations where a short period of missing data is identified. The alternative of basing the patching process on daily (rather than monthly) values was considered but rejected due to the introduction of other potential problems. One of the potential problems is the duplication of high rainfall days due to operators at some stations recording rainfall 1 day out of step (a common problem identified in daily rainfall records within South Africa).

Note that before moving on to step 2 and generating the rainfall inputs to the real-time model, data entry for all stations up to the same date should be completed. This is because the rainfall-runoff model operates for the basin as a whole and will only run up to the earliest data available in the daily rainfall data. If one station has an end date less than the others the rainfall-runoff model will only run to that date.

4.2 Step 2: Generate the rainfall inputs to the model

Figure 11 illustrates that there are three selections to be made related to the storage of the data and the generation of the catchment rainfalls for input to the model (Quaternary catchment coverage, Rainfall station ID attribute and Patched monthly rainfall attribute). In practice these are never changed and are set up before installation of the software. The selections have been left in the software in case changes are made to the SPATSIM application that launches this program. These names are stored within the program initialization file (Drain.ini) located in the SPATSIM/bin folder:

```
[startup]
spini=h:\spatsim\thukela_impl.ini
ptitle=Rainfall Station data
quat=Quaternaries
stat_id=Rainfall Station ID
ts_attr=Catchment Patched Rain
```

The process of generating the inputs to the model begins with patching the station monthly rainfall data. There are two stages to the patching process. The first is to extend the daily data to the end of the current month. This is achieved using a search through the historical rainfall data to find a pattern of similar rainfall and to add a rainfall depth to complete the month. Inevitably, an estimate made after entering 5 days of rainfall will change if a further 10 days real rainfall for the month is added. This facility is required to allow an estimate of the operating rules to be made at the beginning of a month when only a limited amount of that months rainfall data will be available. The second is associated with filling in missing data (-9's) in monthly totals for the individual station data set and this is achieved using up to 5 replacement stations and their associated rainfall scaling factors.

During the development of the software a problem was identified when the data for all stations within a specific part of the catchment are missing. Without some adjustment this would mean that the rainfall input to the rainfall-runoff model cannot be estimated and that the model would not run beyond this point for anywhere in the whole catchment. **The software was therefore adjusted so that the operator is given a warning that this situation has arisen and a mean monthly rainfall value is substituted for the missing value.** The assumption is that this will be a relatively rare occurrence in the long run. It is also possible that in a subsequent data entry period, the missing (caused by a delay in obtaining information from one or more stations) daily data will be replaced by valid data. Under this situation, the revised daily data will update the monthly data and remove the mean monthly estimate.

The only action required by the operator is to click on the ‘Generate Model Inputs’ button and to note any warnings that the software generates. These warnings have been referred to above and mostly relate to possible errors or omissions in the daily rainfall data entry.

For those users who require further detailed information or assessment of the generated rainfall or flow data, it is possible to use the standard SPATSIM facilities to view and analyse the time series. By default (i.e. if the user does not change the names) the station rainfall data are stored within three attributes associated with the ‘Rain Stations’ feature: Daily Rainfall Data (raw data), Monthly Rainfall Data (raw accumulated monthly data) and Patched Monthly Rainfall. The catchment rainfall and generated flow data are stored in two attributes associated with the ‘Quaternaries’ feature: Catchment Patched Rain and GWv3 Simulated Flows.

5. THE REAL-TIME LOW FLOW MANAGEMENT SYSTEM

This part of the report serves as an explanation of the software that has been developed as well as a user manual for the software. The program can be launched from SPATSIM by selecting ‘Application’, ‘Run Process’, ‘Directly’ from the main menu and then selecting ‘Real Time Reserve Management Model’. It can also be run without loading the SPATSIM framework first. The main screen for the software, using the Thukela example, is illustrated in Figure 12.

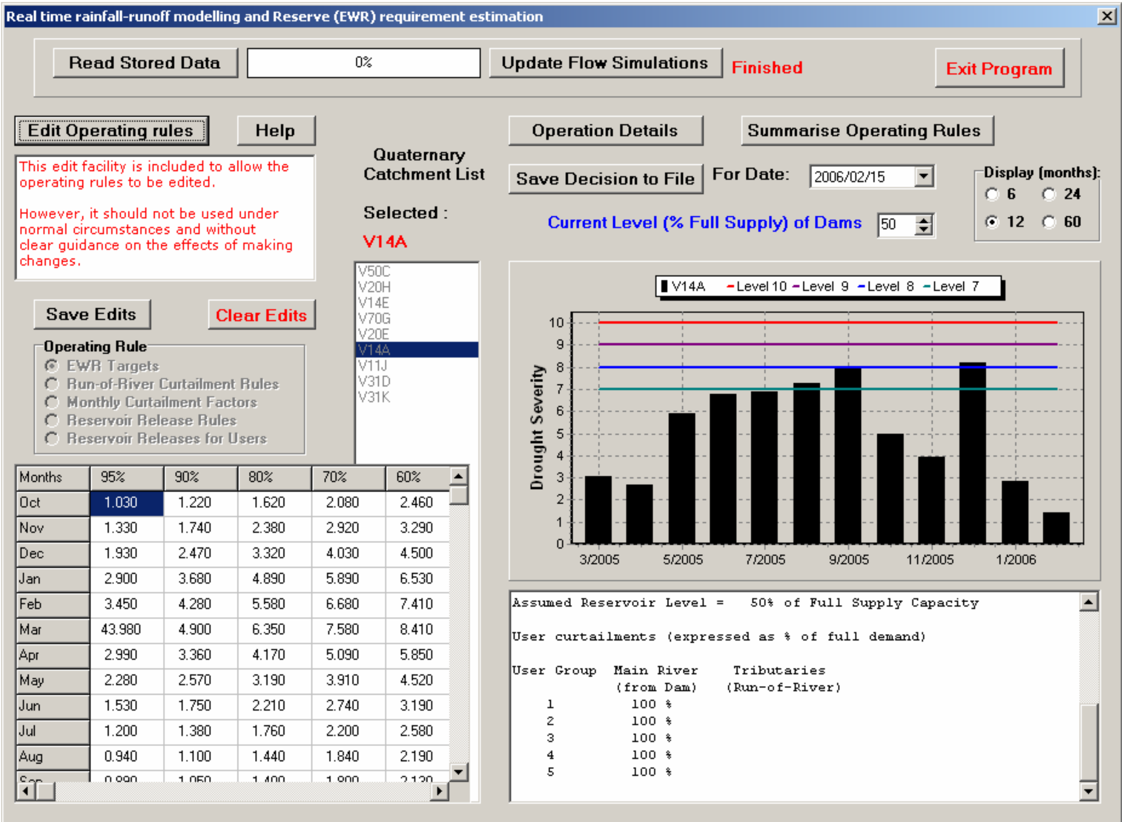


Figure 12 Main screen of the real-time Reserve management model

There are a wide variety of options available within the program, but many of them are used to edit the operating rules which will not be necessary under normal operating situations. These have been included to avoid the necessity of using the SPATSIM data management system to review the information.

5.1 Running the real-time Pitman model

The first step in the process is to update the natural flow simulations for all the quaternary catchments in the basin on the basis of the catchment rainfall data that were generated using the rainfall capturing process explained in Section 4 of this report. This is achieved by clicking on the ‘Read Stored Data’ and ‘Update Flow Simulations’ buttons

at the top of the screen. It is not necessary to click on the 'Update Flow Simulations' button if no new rainfall data were added since the last time this program was run.
The normal user does not have to understand the workings of the Pitman model, nor the parameter values that have been established for the quaternary catchments in the basin. The rainfall-runoff model is therefore a completely 'black-box' component of the management model.

5.2 Selecting the Reserve management area

The list of quaternary catchments for which operating rules are available is provided in the middle-left of the screen. This list represents those quaternary catchments that are at the downstream ends of the identified Reserve management areas. Simply clicking on an item in the list will select the area and all the other data associated with that area.

5.3 Viewing or editing the operating rules

The 'Edit Operating Rules' button can be used to edit one or more of the rules listed in the selection list called 'Operating Rules' (middle-left of the screen). A quaternary catchment must be selected before this button can be used. The different operating rules are explained and illustrated in Section 2 of this report and this information is not repeated here. If further details are required the 'Help' button can be clicked to view some explanations of the different rules. If one set of operating rules is already displayed, these must be saved ('Save' button) or cleared ('Clear') button before a different set can be displayed, or before switching to a different quaternary catchment and therefore a new Reserve management area.

Note that editing the operating rules is not recommended unless the impact of changing these rules is fully understood. Certainly they should not be changed under normal operating situations and should only be revised after any proposed changes are assessed using a system yield model (or similar analysis tool).

5.4 Checking the operation details

The 'Operation Details' button displays the meta-data memo that has been included in the software to capture as much detail of the operation of a specific Reserve management area as is considered necessary. This information can be a very brief summary, or it could include the full details of the water users in the area and their license conditions, as well as the operational basis for making releases from reservoirs. This meta-data is stored within a memo attribute in SPATSIM (with the name 'Res. Impl. Operation Memo' by default) and can be edited using the normal SPATSIM facilities.

5.5 Generating the operating rule information

The 'Summarise Operating Rules' button is used to display the decision support information for a specific period. The period to be displayed is controlled by the date selection box immediately below the button and by the option to choose different durations of display. The default entry for the date selection box is the present day, on the assumption that the rainfall data will be up-to-date. However, it may be necessary to change the date if the rainfall data are not up to date. The graphical display will only go as far as the last month's simulated flow (which is dependent upon the input rainfall data and when the flow simulations were last updated). The selection of different durations display has been included to allow the current month's situation to be seen in the context of the last 6, 12 or 24 months. If the situation over a longer time period needs to be reviewed there is a further option to select the last 60 months (5 years).

The graphical display shows the 'drought severity' for the selected period based on the natural monthly flows compared to the calendar month flow duration curves. The value of the drought severity compared to ranges of flow duration curve % points can be seen if the 'Run-of-River Curtailment rules' are displayed (see Figure 13). In the example provided in Figure 13 it can be seen that a drought severity of 10 represents a natural flow that is equaled or exceeded at least 95% of the time, while a severity of 6 represents flows that are equaled or exceeded more than 70% of the time, but not more than 60% of the time. The horizontal lines in the graph are designed to make it easier to interpret the vertical bars on the right hand side of the graph (i.e. distant from the axis).

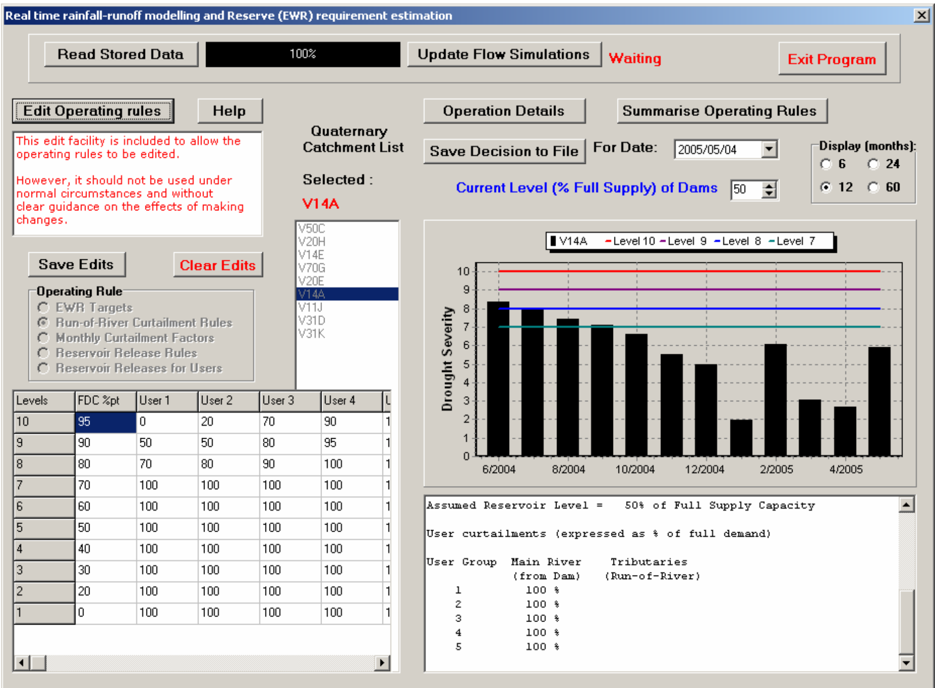


Figure 13 Screen showing the Run-of-River Curtailment Rules'

The real-time model only simulates a representative natural flow time series and does not simulate reservoir levels. Therefore, to allow the reservoir release rules to be applied correctly it is necessary for the user to set the value of the current level of dams. A simple 'spin-edit' button with 5% increments is used for this purpose.

5.6 The operating rule information and decision support

The Reserve requirement estimates are interpolated between the current month and either the previous month, or the next month if the date specified is within the first or last 10 days of the month. In other respects the selected day is not very relevant. Table 18 illustrates the type of information that is generated in the display at the lower right part of the screen and that is written to a file if the 'Save Decision to File' button is clicked. The information includes the reservoir releases for the Reserve and downstream users with and without any curtailments. It also includes the details of the recommended curtailments for each of the 5 possible user groups supplied from reservoir releases or from run-of-river flows.

Table 18 Decision support information example

[illegible]

The assumption is that the information contained within Table 15 is sufficient to allow a water resource manager, or senior reservoir operator, to make a decision. In the case of the run-of-river user curtailments it is assumed that some form of communication system is available to notify users that a specific level of drought condition is prevailing and that they should reduce their abstractions in accordance with their license conditions.

It is necessarily further assumed that the curtailment rules that are used within the software are part of any agreements reached with water users or are part of their license conditions.

6. THE REAL-TIME HIGH FLOW MANAGEMENT SYSTEM

As already indicated the rainfall input data to the high flow management system is based on the same data as the low flow management system and therefore the rainfall data capture software also applies to this system. The main difference is that the data would need to be collected and captured more frequently if the high flows are to be triggered appropriately.

It should also be pointed out that the authors are not satisfied with the results of testing the high flow release trigger system, but alternatives that were considered were more difficult to use and did not appear (in the example case of the Thukela) to generate any better results.

Figure 14 illustrates the design of the software that has been developed to apply the model in practice. It is designed as an external model to SPATSIM with input requirements for each of a group of quaternary catchment polygons as follows:

- Catchment ID. A text attribute containing the name of the quaternary catchments.
- Rain Stations for Patching. A memo attribute that contains the list of 5 rainfall station names that will be used to generate the weighted CPI values. The name of the point GIS coverage that contains these stations is referenced in the .ini (initialization file) for the software program.
- Rain Patching Parameters. The recession coefficients and weights for the 5 stations referred to in the last bullet point, stored in an array attribute.
- Flood Release Rules. An array attribute holding up to 20 rows of information as illustrated in Table 15.
- History of Releases (Flows). A daily time series of historical releases calculated from the historical CPI data using the 'Historical Releases' button.
- History of Releases (Events). A daily time series containing the flood number (see Table 15, column 1) for every day that historical releases are calculated.
- Management Releases (Flows). A daily time series of flows that were released based on the release decisions.
- Management Releases (Events). A daily time series containing the flood number based on release decisions.

The last two time series outputs are based on the 'forecast' CPI and management decisions taken about when and how much to release. They therefore differ from the previous two outputs (based on historical data estimates) in that the CPI 'forecasts' will never be the same as the CPI values based on real rainfall and the management releases can be influenced by user intervention in the release recommendations. The SPATSIM TSOFT utility can be used to display the two sets of time series and compare the results.

The left hand side of the screen is used for selecting the Reserve management zone (based on the most downstream quaternary catchment for each zone), noting which rain stations have been selected for generating the CPI, selecting the date for a Reserve estimate (the last day of existing rainfall information, by default), generating a rainfall forecast, setting the release criteria (see Figure 9) and generating historical releases.

The right hand side of the screen is used to display the calculated CPI time series, as well as the 10 days of CPI based on the ‘forecast’ from the current day (the date given in the ‘Estimate for’ date box). The lower graph generates a value representing the probability of a release being recommended for each of the 10 days of the forecast period. This could be useful to warn operators of a possible release in the near future. However, it must also be recognized that a ‘forecast’ a few days later may give a different result. The ‘Release Decision’ button takes the user to the more detailed information on the characteristics of any release that will be recommended for the present day.

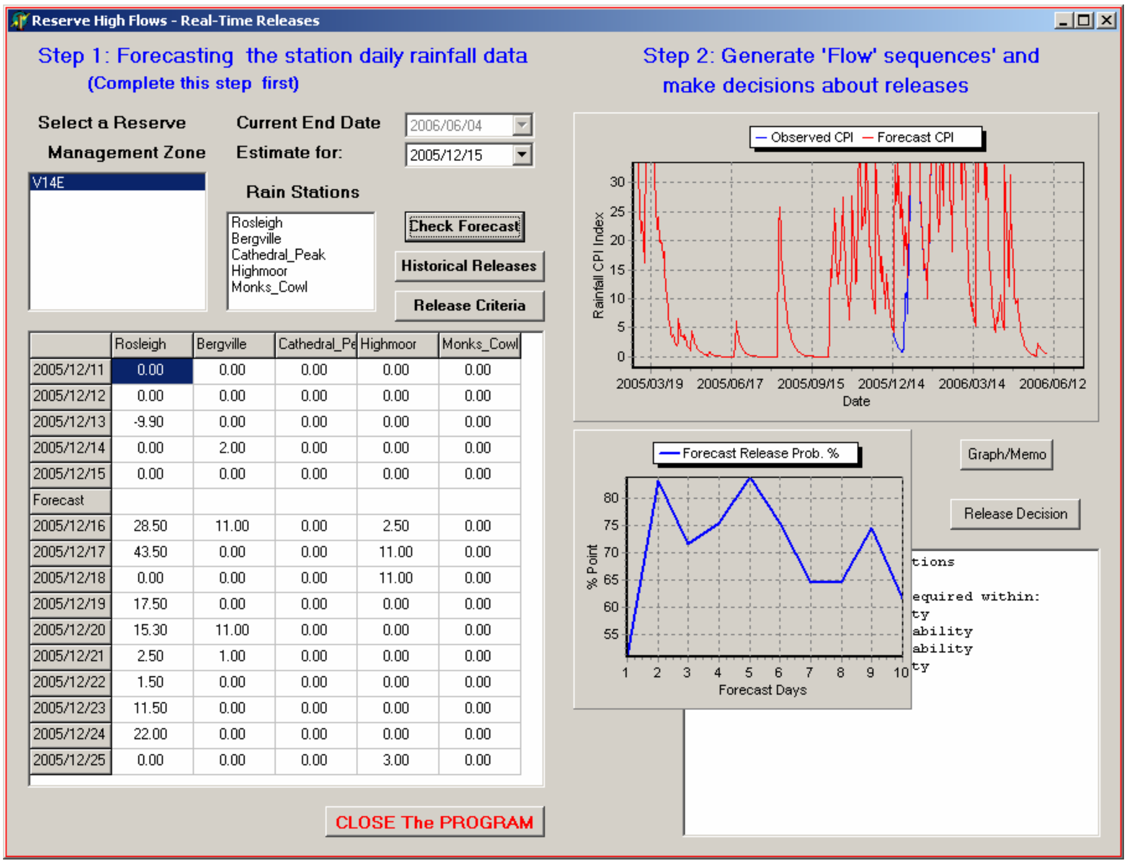


Figure 14 Main screen for the real-time Reserve high flow release model (see text for further details)

6.1 Release decision making

The ‘Release Decision’ button is activated after a ‘forecast’ is made (using the ‘Check Forecast’ button) for the same day as the last day of the daily rainfall time series (this means that the two date boxes should show the same date). The release recommendation is based on the CPI value for the present day (using the historically measured rainfall data) and the CPI value for the first day of the ‘forecast’. The methods of estimating which event to recommend (Table 15, for example) and how large the event should be are identical to the methods used for the historical release determination. This implies that those releases that were accepted have to be stored for later use (in the Management Release time series) as they may affect later decisions.

Figure 15 shows the Release Decision Making screen. Assuming that a release has been recommended, the first decision level consists of a choice between not releasing any event, accepting the 'forecast' decision and specifying an alternative event.

If the 'forecast decision' is accepted the program automatically decides on the event category and event number (based on the two CPI inverted % point values, the month and the selection criteria shown in Figure 9) and shows a brief summary of the result in the memo at the bottom of the screen. The user can then either accept this event or reject it and make a different decision. If the event is accepted, the results are saved to SPATSIM in the Management Release time series, the release event is further split into 3, 6, or 12 hour interval releases and the results displayed in the memo at the top right and the graph at the bottom right. The choice of the interval is based on the total duration of the event (see Table 15) as specified in the Reserve high flow event table. The division into intervals ensures that more than 15, but no more than 30 separate intervals are specified. This approach has been based on the production of a relatively smooth release without being too complex for the reservoir operators. The table of values can be printed for later reference when managing the release event. It has been assumed that decisions will be taken early in the morning after the previous days rainfall data has been collected and entered in the system (using the program described in Section 4 – daily rainfall data capture process). The release timing has therefore been assumed to start at 12h00 on the decision day. The table of values and times are, however, only guidelines for the operator and it is quite possible that a similar but slightly modified release system will be used in certain circumstances. It is, however, important to recognize that a relatively smooth pattern of flow changes should be achieved wherever possible.

If the option to 'override' the 'forecast' decision is made, the user is given the choice of one or more events that are appropriate to the current month and can then specify a peak value (see Figure 16). The analysis proceeds from that point onwards in the same way as if the decision had been made to accept the 'forecast'.

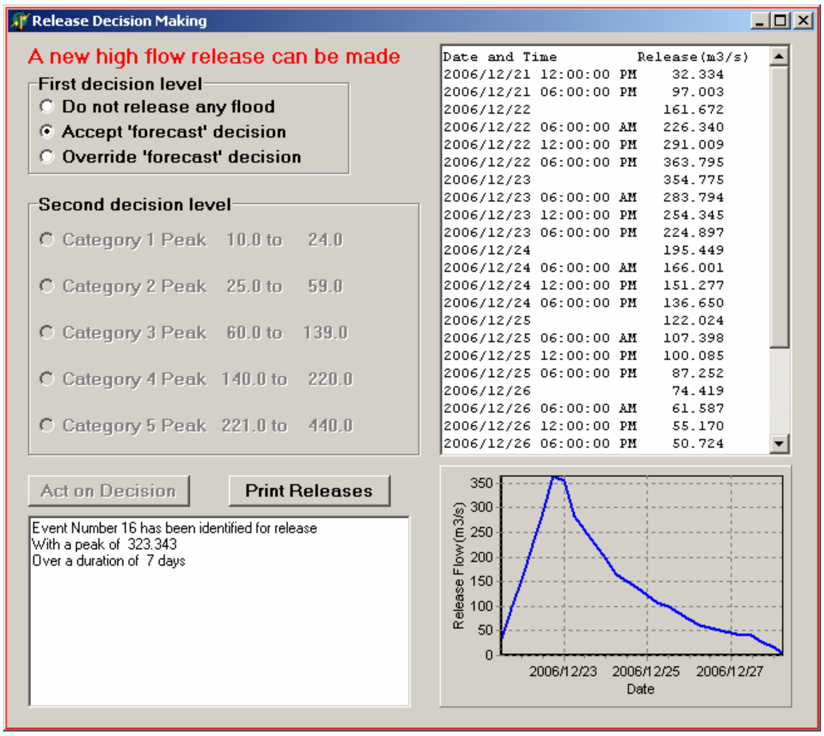


Figure 15 Release Decision Making Screen

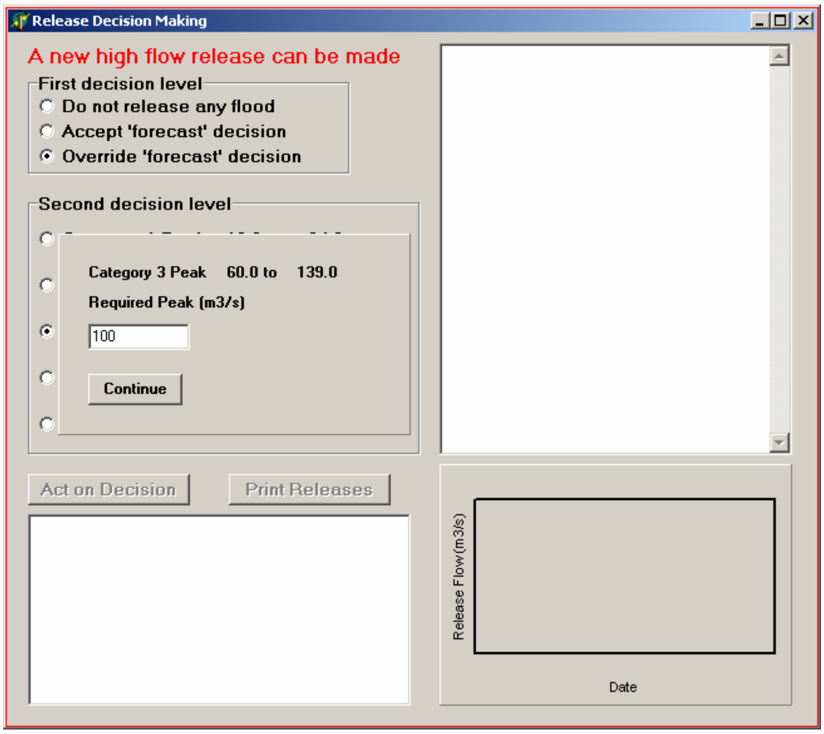


Figure 16 Release Decision Making Screen – with ‘override’ option

6.2 General observations

The whole basis of the research work related to high flow releases was to identify existing methods that could be used or readily adapted, and failing that, to base high flow release decision rules on easily available data and simple procedures. The project has indicated that there are two sets of issues that need to be addressed – design issues that can be resolved as part of the implementation design and operational issues that are part of the real-time decision making process.

The design issues are primarily concerned with translating the high flow requirements, defined during a Reserve determination process, into release specifications. The issues to be considered are what proportion of the downstream event requirement is likely to be satisfied by tributary inflows (given that the release timing is satisfactory) and what are the loss and flow attenuation properties of the channel system between the release point and the requirement site. It has been concluded that existing methods effectively already exist to address these issues (Section 3), even though some of the methods may need to be calibrated with test releases during the early phases of implementation.

If it is assumed that this additional 'design' work will be undertaken by a specialist hydrology consultant, there is little doubt that there are financial implications that would increase the cost of a Reserve determination. However, it also has to be remembered that the additional design work for high flow implementation is only required when a reservoir exists (or is to be constructed) with outlet works that can be used to manage the releases. In all other cases the high flows are assumed to occur semi-naturally.

The operational issues are associated with when to release and the relative volume (or rate) to release. This report has illustrated that an approach can be designed that is based on relatively simple rules and requires very little data. However, there are two factors that will strongly affect the efficacy of the approach that need to be clearly recognized:

- The method proposed and incorporated into the software relies upon reasonably accurate daily rainfall data being available in the immediate past (the last 24 hours prior to a release decision being made). It is apparent from the existing data collection procedures in the Thukela that this will not always be possible and that there will be many occasions when some of the required rainfall data will not be available. If any effective real-time operational management process is to be established then this issue needs to be addressed with some urgency. It is a sad indictment of the South African hydro-meteorological data collection system that it is not possible to obtain reliable information on the primary input (rainfall) to the natural processes that determine our water resource availability.
- The second issue relates to the 'forecasts' for the day ahead. It has not been possible during this project to find a really suitable method for generating these forecasts with an acceptable degree of reliability. The method used in the software that has been developed is a simple and pragmatic alternative that needs to be replaced with a better method as soon as possible. There are many resources being expended on climate research in South Africa and it is surprising that the issue of real-time water management has not been adequately addressed. It is possible that suitable 'forecast' products are available and that the participants in this project are simply not aware of them. However, if that is

the case then these products need to be better advertised and made more widely available.

The ultimate test of any real-time operational system is through its practical application. This has not been possible during the limited time available for this project and has been constrained by the apparent lack of 'readiness' to implement the Reserve. The project team believes that some form of practical testing is an urgent requirement.

7. EXAMPLE APPLICATION – THUKELA BASIN

The Thukela River basin has been used throughout this project as the main example through which the methods were developed and tested. The deliverable reports referred to in the introduction therefore contain detailed information related to the different parts of the Thukela basin. This section is included to summarise the way in which the low flow management system was set up, as well as the reasons, which were strongly influenced by the current management capabilities. A large part of the information used for the Thukela basin was generated during the Reserve determination component of the Thukela Water Project (see DWAF, 2004b), while additional information was generated through data analyses undertaken as part of the WRC project.

Figure 5 illustrates that 11 Reserve management areas were identified within the Thukela basin. Deliverable report D provides the full information on the operating rules for these 11 areas and they are summarised below. ***One general observation is that without further management capacity, which may only be achieved with the implementation of compulsory licensing, the system cannot be operated optimally.***

7.1 Zaaihoek dam catchment – V31D

Zaaihoek dam is managed by the Gauteng region and it was made clear that there are no immediate plans to include the Reserve in the management of this system. Although Reserve releases were determined by this project, it was assumed that they will not be implemented at this stage.

7.2 Ntshingwayo (Chelmsford) dam catchment – V31K

The irrigation releases required from Ntshingwayo Dam, based on the WARMS database, are very limited and it was assumed that these are released as a continuous release. The large requirements of the Ntshingwayo Dam are those of Newcastle and the surrounding towns as well as Iscor. The releases from Ntshingwayo for ecological requirements were based on an initial assumption of 46% of the ecological flow requirement at V31K. While no curtailments are required of any users in order for the ecological flow requirement to be met at V31K, the releases made from the dam will be much larger than assumed in all previous planning studies, with the result that there will be little or no surplus yield from the Ntshingwayo Dam.

7.3 Lower Buffalo River catchment – V33B

There are some large unlawful users on the Buffalo flats near Dundee. It is assumed that the Regional Office cannot curtail these users at present. This unlawful water use was estimated to be in the order of 10 $*10^6$ m^3 y^{-1}. It was decided that no additional releases should be recommended from Ntshingwayo or Zaaihoek to account for these water users, but the potential problem will be flagged for future attention. The implication is that the Reserve at site 14 in the Buffalo River will probably not be met and that potential contributions from the Buffalo River to the Reserve requirements in the lower Thukela River will have to be ignored.

7.4 Sundays River catchment – V60F

According to the WARMS database there is very little irrigation in the Sundays River catchment and the ecological Reserve can be met without applying any curtailments to users. Previous estimates of irrigation requirements indicated substantial irrigation in this catchment and this is a factor which will need to be investigated during the implementation of the Reserve model. This site is therefore not currently included in the implementation model.

7.5 Upper Thukela, Woodstock dam – V11J

In practice releases are made from Driel barrage for the substantial (27.8 * 10^6 m^3 y^{-1}) irrigation downstream of the dam and the ecological Reserve. However, the DWAF Regional Office has indicated that much of this irrigation is unlawful and that releases will not be made for them in future. White Paper WP – R'74 gives the compensation release as 8.77 * 10^6 m^3 y^{-1} and this revised release has been used in updating the releases for ecological purposes. Since very large abstractions (up to 19 m^3 s^{-1}) are made from the Driel Barrage, releases are made almost continuously from the Woodstock Dam to support these large abstractions. In reality therefore, support to irrigators and the ecological Reserve is from Woodstock. The assumption is made that the full 8.77 * 10^6 m^3 y^{-1} is released continuously from Woodstock while the release for the Reserve was based initially on 62% of the ecological Reserve requirement at IFR1. The remaining 38% is supplied by incremental inflows downstream of Driel Barrage, as well as spills.

In order to ensure that there is sufficient water reserved in Woodstock for the Reserve, curtailment levels must be set beyond which transfers to the Vaal out of Driel Barrage must cease completely. A minimum level of 5% of the full supply capacity will suffice for all months of the year.

While it is recognised that the Gauteng Regional Office of DWAF will not be managing the releases for the Reserve according to the specifications given in this report and included in the model, this is not expected to impact on the releases that are recommended to be made from Spioenkop Dam for the Reserve at IFR4, largely because there is sufficient spare capacity in Spioenkop at present.

7.6 Little Thukela catchment – V13E

The DWAF Regional Office has indicated that until compulsory licensing has been implemented in the Little Thukela catchment it would be very difficult to implement the Reserve through curtailment of irrigators. For the purposes of determining the required releases from Spioenkop for IFR4, it was therefore assumed that irrigators are not curtailed in the Little Thukela catchment. This essentially implies that additional releases are made from Spioenkop to account for the lack of compliance with the Reserve within the Little Thukela and the contribution that this tributary would otherwise have made to satisfying the Reserve at IFR4.

7.7 Bushmans River catchment – V70G

The full irrigation requirement of 19.8 * 10^6 m^3 y^{-1} is supplied from Wagendrift Dam as a seasonally varying release, while the release for the ecological Reserve was based on an initial assumption of 71% of the ecological flow requirement at IFR6. Curtailments are not considered necessary.

7.8 Middle Thukela, below Spioenkop dam – V14E

It is assumed that the irrigators downstream of Spioenkop Dam, up to and including IFR site 4, will be supplied fully and continuously from Spioenkop Dam. It is never necessary to curtail these users since Spioenkop Dam is operating well below its firm yield and is in no danger of emptying. The urban requirements of Ladysmith and the surrounding towns are also met from Spioenkop.

Releases to be made for the Reserve from Spioenkop Dam have been based on an initial assumption of 80% of the ecological flow requirement at IFR4 (see Table 9), while releases for all downstream users are provided in Table 10.

This is the area which was originally identified for operational testing of the model outputs in real-time. However, it is difficult to identify a site where the success of these release rules can be adequately monitored, mainly due to the lack of a gauging site at IFR4. An approximate assessment can be made using the gauging data at V1H001 (Colenso Weir – at the outlet of V14A) and a Reserve extrapolated upstream to this location from IFR4. The alternative is to monitor the results for the whole basin at gauging station V5H002, as the releases made from Spioenkop are designed to cater, together with tributary inflows, for the lower part of the basin as well.

7.9 Upper Mooi River catchment – V20E

Quite severe curtailments (Table 19) will be required to irrigators upstream of the Mearns Weir in order to meet the ecological Reserve at IFR11. These curtailments are severe in the drier winter months and might be difficult to implement without compulsory licensing. It is recommended that the Reserve only be implemented in the Mooi River catchment when the Springrove dam has been completed and that this dam be used to regulate flows for the purpose of the Reserve.

Table 19 User curtailment rules (% of demand) for the region above IFR11

FDC % Point	100%	85%	70%	50%	0%
Oct	0%	20%	50%	70%	70%
Nov	50%	80%	100%	100%	100%
Dec	100%	100%	100%	100%	100%
Jan	100%	100%	100%	100%	100%
Feb	100%	100%	100%	100%	100%
Mar	100%	100%	100%	100%	100%
Apr	50%	80%	100%	100%	100%
May	0%	20%	50%	70%	70%
Jun	0%	20%	50%	70%	70%
Jul	0%	20%	50%	70%	70%
Aug	0%	20%	50%	70%	70%
Sep	0%	20%	50%	70%	70%

The storage within the Mearns Weir is too limited to develop curtailment rules for the transfer to the Mgeni system based on the state-of-storage in the weir using a monthly model. A daily or weekly model would be required for this. The alternative was to base curtailments on the natural flow signal at IFR11. An operating rule was developed by trial and error based on an initial assumption that 84% of the Reserve requirement must flow past the Mearns Weir. This rule was not very successful and requires further refinement. It is not considered necessary to curtail irrigators downstream of IFR11. The operating rules are far too complex for the current version of the real-time model and this issue will have to be addressed at a later stage after further discussion with the Regional Office staff. However, it is not intended to apply the model at this site in the immediate future.

7.10 Lower Mooi River and Craigie Burns dam – V20H

Irrigators on the Lower Mooi first use what is available from run-of-river, after which releases are made from Craigie Burn. No curtailment is required to irrigators downstream of the confluence of the Mooi and Myamvubu rivers. The releases required for users are highly variable and have not been included in the model at this stage. Releases made for the Reserve at IFR12 from Craigie Burn Dam were based on an initial assumption of 50% of the ecological flow requirement.

7.11 Lower Thukela River – V50D

No curtailments appear to be necessary (under current levels of abstraction) to substantially meet the ecological Reserve at IFR16. This result is related to the fact that upstream management controls appear to be sufficient to satisfy the Reserve requirements at this site. This site has been included in the model setup so that the full low flow Reserve requirement at IFR16 (V50C) can be compared with gauged flows at V5H002.

7.12 General observations

There are still a number of issues that need to be resolved before the real-time model parameters (within the upper Thukela and lower Buffalo River, for example) can be considered to be finally quantified. However, there appears to be general acceptance that the rules are now adequate for initial testing in practice. The rule parameters of the real-time model have been updated and the model is ready for further assessment by the DWAF KZN Regional Office. It has been decided that initially the application and assessment of the model will be restricted to releases from Spioenkop Dam. The assessment will be based on monitored flows at V1H001 and V5H002. It will be necessary to keep records of the releases made so that these can be compared with the model recommendations and the gauged flows. It will also be necessary to bear in mind the fact that many parts of the basin will not be initially managed according to the rules used in the systems model and transferred to the real time model. This means that un-accounted for users may be one of the reasons why specified design releases do not meet the Reserve objectives at a particular monitoring site.

8. EXAMPLE APPLICATION – KOUGA BASIN

The catchment discretisation used in previous water resources studies was retained for this study. The reason for this is that these studies are the source of the most reliable hydrology and water use data. The catchment and its sub-division are shown in Figure 17.

The hydrology derived from previous DWAF studies was used for modelling the water resources of the Kouga catchment. This hydrology is summarised in Table 20. For comparison purposes, the WR90 and alternative updated volumes are also shown. The updated hydrology referred to here was sourced from work done for DWAF by Ninham Shand (Inc.) to recalibrate the hydrological models in the Kouga catchment. This new hydrology results in much higher yield estimates for the Kouga Dam and in order to be consistent with yield estimates which have been quoted in recent reports which are in the public domain, it was decided not to use the updated hydrology for this study.

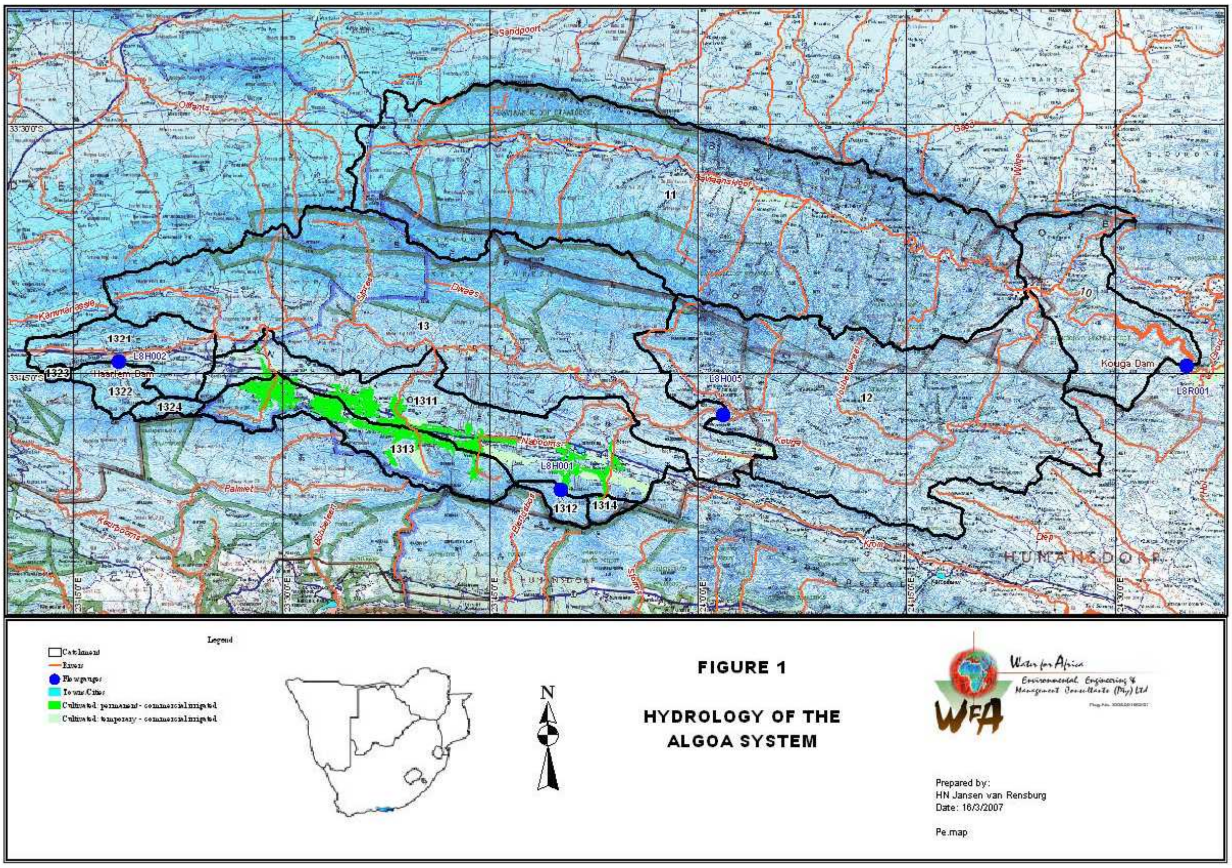


Figure 17 Kouga River basin

Table 20 Summary of the Kouga River hydrology

Catchment		Mean Annual Runoff (million m^3)		
Algoa prefeasibility study (DWAF, 1996)	WR90	Algoa prefeasibility study (DWAF, 1996)	DWAF, 2004a	WR90
1311		9.5	16.6	
1312		11.8	14.6	
1313 & 1314		28.4	28.3	
1321		10.8	17.4	
1322		12.7	12.2	
1323 & 1324		6.7	7.4	
13		47.2	75.3	
Sub-total	L82A to D	127.1	171.8	106.5
10	L82H	5.8	4.0	
11	L81C to D	33.5	24.1	
12	L82E to G	19.7	15.6	
Total		186.1	215.5	194.0

8.1 Dams in the Kouga catchment

The catchment under consideration in this study flows into the Kouga Dam. The only other significant dam in the catchment is the Haarlem Dam located in the upper reaches of L81A catchment. There are a large number of farm dams in the L81A and L81B catchments, some of which are off-channel. To carry out a complete inventory of these dams and find out how each dam is operated (i.e. whether they are off- or on-channel) would be a very time consuming task. For the purposes of this study therefore, the simplifying assumptions made in the pre-feasibility study were used. In this study, the farm dams are represented by two dummy dams, the characteristics of which are given in Table 21.

Table 21 Characteristics of the dams in the Kouga River System

Name	River	Gross Capacity (million m^3)	Catchment Area (km^2)	Virgin Mean Annual Runoff (million m^3)
Haarlem Dam	JordaansRivier	4.75	21.8	7.2
Dummy dam 1 (representing all farm dams in the middle Langkloof catchment)	Kouga River	13.54	156.6	28.6
Dummy dam 2 (representing all farm dams in the lower catchment)	Diep River, Louterwater River	15.12	508.6	49.5
Kouga Dam	Kouga River	128.68	2820.0	135.5

8.1.1 Kouga Dam

The Kouga Dam, formally the Paul Sauer Dam, was constructed in the early 1960's primarily to supply water to irrigators along the Gamtoos River. However, an allocation was also made to Port Elizabeth. The current allocations are as follows:

- Irrigation: 59 million $m^3\,y^{-1}$
- Urban (Patensie and Hankey): 3 million $m^3\,y^{-1}$
- Urban: Port Elizabeth: 23 million $m^3\,y^{-1}$ (also supplied from Loerie Dam)

The Kouga Dam cannot meet all these water demands and most of the time the irrigators receive 43 million $m^3\,y^{-1}$. The latest operating rule is that irrigators may only utilise their full allocation of 59 million $m^3\,y^{-1}$ when the Kouga Dam is spilling. Port Elizabeth abstracts their allocation from the Loerie Dam which has a yield of about 6 million $m^3\,y^{-1}$ but is fed from the spills from the canal which supplies the irrigators. On average this spillage is approximately 18 million $m^3\,y^{-1}$ so it is seldom necessary to release additional flow from the Kouga Dam for Port Elizabeth.

8.2 Water Requirements

For the purposes of operationalising the Reserve, users in the catchment need to be categorised in terms of their assurance of supply. In the case of the upper Kouga River the only significant water user is the irrigation sector. A typical curtailment rule for the irrigation sector is shown in Table 22. It is assumed that the ecological Reserve must be met all the time and that water users will be curtailed, or releases made from dams in order to achieve compliance with the Reserve. The Ecological Reserve is therefore not listed as a user in the table.

Table 22 Proposed curtailment levels of irrigators in the Kouga basin

User group	% of time curtailment level is equaled or exceeded	% of full requirement supplied
Irrigation	0 to 50%	100%
	50 to 70%	80%
	70 to 90%	50%
	90% to 100%	30%

The Kouga can be sub-divided into three Reserve management areas (see Figure 17): the middle Langkloof (1321, 1322 and 1323); the lower Langkloof (1311, 1312 and 1313) and the remainder of the Kouga basin. The water users in each management area are given in Table 23 and all irrigators are assumed to be supplied from the two dummy farm dams that have been included in the system yield model. It is likely that some of the irrigators are supplied from run-of-river abstractions but detailed information on the source of supply of each irrigator was not available to this study, although it has apparently been collected as part of the process to declare this catchment a Government Water Control Area. It is interesting to note that the 2002 DWAF report refers to irrigation from the Haarlem dam, while no reference to this is made in the later 2004 report. The latest (2000) DWAF landuse coverage which was used to populate the irrigation area shown in Figure 17 does not include any irrigation that could benefit from supply from the Haarlem dam.

Table 23 Water users in the Kouga dam catchment (Mill. $m^3 y^{-1}$)

User group	Middle Langkloof	Lower Langkloof	Remainder
Diffuse irrigation	0.0	1.5	0.4
Farm dam irrigation	13.7	21.0	0.0

The ecological Reserve requirements were determined using the Desktop model and equate to 16.1%, 22.6% and 16.3% of natural mean annual runoff for the three areas referred to in Table 23.

8.3 Operational choices

In practice, there would be two choices for ensuring that the Reserve requirements are met. Either river abstractions can be curtailed or releases can be made from some of the off- or on-channel dams. In the case of off-channel storage, it is assumed that pumping would only be allowed when flow is in excess of the contribution required from that part of the catchment to meet the Reserve.

Even if the Reserve requirements are supplied by additional releases from the dams, it is still necessary to apply curtailment rules for irrigators supplied from the dam so that the dam does not reach zero storage during dry periods. These curtailment rules were derived by trial and error and summarized in Table 24.

Table 24 Curtailment rules for irrigators supplied from farm dams

Water level in the farm dams (% of full supply volume)	Supply to irrigators (% of full demand)
100 to 80%	100%
80 to 50%	80%
50 to 30%	50%
< 30%	30%

8.4 General observations

No attempts have been made to set up the real-time rainfall capture process and identify the reporting raingauges. However, this is likely to be a difficult task given the relatively inaccessibility of the steep topography areas of main runoff generation. Table 20 illustrates the uncertainties that exist in the natural runoff estimations in this basin which is largely ungauged. This is likely to present further problems in not only setting up the real-time rainfall-runoff model, but also in determining accurate yields and acceptable operating rules. There are also a number of uncertainties associated with defining the existing water use, the source of that water and therefore the management options available.

Despite these problems the basic information requirements to establish the low flow component of the real time system have been quantified for the Kouga River catchment. Before these could be used effectively it would be necessary to:

- identify the real-time reporting rainfall stations that can be used,
- re-calibrate the Pitman model using this rainfall information and establish the parameters of the model for real-time generation of natural flow signals,
- confirm and adjust the details of the sources of water used by the irrigators,
- assess whether the initial operating rules can be considered appropriate (through consultation with the users),
- perform some preliminary tests to ensure that the frequency of curtailment is not likely to have excessive economic and social impacts.

9. CONCLUSIONS AND RECOMMENDATIONS

Throughout this report it has been assumed that the management of the Reserve and the management of water supplies are inextricably linked. They cannot (and should not) be separated during the planning phase of any water resource development and should not be separated during the implementation, or operational phase. The approaches that have been proposed during this project have been developed with the recognition of this principle. This means that the Reserve and water use are treated in much the same way and neither is assumed to be constant and unvarying. The Reserve is designed to be like this, based on the precept that maintaining some flow variability will be beneficial to the ecological functioning of the river system. The variability in supplies to water users is not beneficial and is potentially damaging to the social and economic functioning of the water use sectors. However, this variability and the necessity for curtailments to normal use are direct consequences of competition for water use in a country that has relatively scarce resources and a variable climate. The alternative would be very small allocations that could be supplied constantly without any shortfalls. This would be the case in many catchments whether the Reserve is supplied or not and is unlikely to be either socially acceptable or economically viable (see Hughes and Mallory, 2007 for further discussion). This issue is being investigated further within a DWAF project on operationalising the Reserve.

The examples provided in this report have been based on the best information available to the authors at the time of writing. It is very clear that this information is normally inadequate to design an operational system that is optimal from the point of view of the Reserve as well as the socio-economic consequences. The research team was frequently faced with making decisions about how to distribute curtailments without any information from the water users this might affect, nor any real information about whether these curtailments could be effectively applied. In some situations it was made quite clear by the relevant DWAF regional office staff that it would be impossible to impose some of the suggested operating rules (i.e. curtailments) on existing users, given current legislation and management capacity.

There have been quite a lot of developments in recent years of methods designed to assess the ecological impacts of different flow scenarios. While they may still lack precision, due to the lack of scientific understanding of the relationships between flow and ecological functioning, procedures are nevertheless available. The same is not true of procedures to assess the impacts of different operating rules on various water user sectors (Hughes and Mallory, 2007). There have been various socio-economic assessments but there do not appear to be clear guidelines on methods that are considered acceptable to the broad community of water users and managers. The success of the approaches developed during this project for implementing operating rules is very dependent upon the design of those rules. If the methods for designing the rules are not available, or not acceptable to water users, the whole implementation system will not be viable. The implementation system will also not be viable if water management agencies do not have the legislative support or the capacity to enforce operating rules.

The project team has developed several recommendations that they believe are critical if the approaches outlined within this report are ever likely to be used as a part of operational water resource management within South Africa.

9.1 Impacts of different operating rules

To be able to effectively design the operating rules for both the Reserve and for water users it is necessary to have impact evaluation systems that can be effectively compared. This is not an easy task as the 'value' systems (measures of beneficial water use) are likely to be different for different water users and are certainly different between the Reserve and most water users. This recommendation requires the input of resource economics, social economics and other relevant specialists. It is essential that these specialists understand the possible water management options that are available and incorporate these into the evaluations. One example is that evaluations based on normal water requirements and use is unlikely to be sufficient and that they should account for the impacts of periodic shortfalls in supply (Hughes and Mallory, 2007). The evaluations also need to be reduced to a common denominator, or comparable impact measure, so that comparisons can be made across water use sectors, including the Reserve.

While the need for these impact assessments does not affect the generic design of the implementation methods, they do affect the way in these methods are applied in practice.

9.2 Implementation of operating rules

The problems related to the implementation of operating rules and the enforcement of curtailments has already been referred to. It is recognised that the capacity to enforce water restrictions is currently very limited and will probably remain so until all the provisions of the legislation associated with compulsory licensing are in place and fully functioning. Even then, users may have curtailment conditions attached to their licenses to abstract water but may ignore any demands by the water management agency to apply these restrictions and decide not to comply. It is recognised that the type of real-time management of water resources that is proposed in this report is a departure from past practice. However, it should also be recognised that past (and even current) practice is largely based on water management legislation that no longer exists. If the principles of the new Water Law are to be applied in practice, and especially in water stressed catchments, compulsory licensing and the design of operating rules that include curtailments is unavoidable. If the practical application of the Water Law principles is to be successful those operating rules need to be enforced.

The methods and the software that have been developed as part of this project are relatively straightforward to implement. If the issues associated with the equitable design of the operating rules discussed in Section 9.1 are addressed, there should be no reason why these methods cannot be applied if the community of water users and water managers are 'willing' to ensure that they work in practice. Without that 'will' they are very unlikely to succeed. Either the Reserve requirements will not be met, or some users will not be able to access the water they have been allocated, because other water users fail to comply with their license conditions.

In stressed catchments where there is competition for limited water supplies, particularly during drought periods, if a system that is broadly similar to that presented in this report is not implemented it is apparent that equitable water management will not be possible. It is in the long term interests of all water users to voluntarily comply with the implementation of operating rules similar to those referred to in this report. However, it is necessary to ensure that water users are fully involved in the decision making process at the beginning when the operating rules are designed and their impacts assessed. It is clearly understood that getting 'buy in' from water users is a great deal easier if they are part of the decision making process than if they are forced to comply with a decision made by someone else.

9.3 Impacts of changes in patterns of climate variability

The low flow management system is partly based on operating rule triggers using natural flow time series. The actual triggers rely upon the comparison of an estimate of natural flow during the decision making period with the long term flow duration curve of the natural flow regime. The assumption is that the historical flows used to generate the flow duration curves are stationary. If future patterns of climate variability are different, this assumption may no longer hold. For example, if rainfall were to generally decrease, future flow estimates would always fall on the drier part (lower flows, higher % exceedence) of the duration curves. The implication is that more frequent drought periods would be predicted and that curtailments would be required more frequently.

While this may be an appropriate result (in that reduced rainfall will lead to reduced runoff and therefore reduced water supplies), it will probably be for the wrong reason. A better approach would be to generate a revised historical rainfall time series (using a suitably reliable climate model) and re-generate the historical reference runoff time series, using the rainfall-runoff model, to reflect the new 'natural' conditions due to the new climate conditions. It may be necessary to make appropriate changes to other components of the rainfall-runoff model, such as land cover parameters and evaporation demand data. This 'natural' time series would then need to be used with an appropriate systems yield model to determine revised operating rules and a revised Reserve that can then be incorporated into the real-time model.

Clearly it would be necessary to be certain that any reductions in rainfall that are detected are really a result of a long-term change in climate patterns and not simply a short-term perturbation. This, in itself, may prove to be a difficult task and very prone to subjective assessment.

9.4 Monitoring

This report has said very little about the issue of monitoring. There are essentially three types of monitoring that are required. The first relates to water users and monitoring their compliance with the conditions of their abstraction licenses. This is probably the most difficult and requires quite substantial resources on the part of the water management agency. Community self-monitoring should therefore be encouraged wherever possible. This would involve the community of water users monitoring the compliance of individuals who are part of that community.

The other types of monitoring refer to the Reserve and involve determining whether the flow requirements of the Reserve are being met (flow monitoring) and whether those flow requirements are achieving the ecological objectives that were defined as part of the design (biological monitoring). Both of these involve long-term monitoring programmes and various recommendations have been made in the past as part of Reserve determinations undertaken for specific river systems.

9.5 Critical assessment of the project results

In general terms the members of the project team are satisfied with the outcomes of the project and are reasonably confident that the methods and software that have been developed are based on sound principles and can be applied in practice. This level of confidence is higher for the low flow components than for the high flow components. The project team is satisfied with the initial responses to the developed approaches from the water resource management community and their inputs were valuable. However, the project has failed to properly test the developed systems in a real situation and this need to be addressed in the near future.

Internationally, there appears to be an increasing level of interest in the implementation of environmental flows as part of integrated water resource management. It is therefore important that contributions from South Africa are communicated to other countries so that our approaches can be appraised and considered together with other suggestions.

The members of the project team are also involved in a Department of Water Affairs and Forestry project on 'Development and pilot implementation of a framework to operationalise the Reserve', which began at the end of 2006. There are clear overlaps between the WRC project just completed and the DWAF project that has just started. It is important that the concepts, methods and software that are contained within this report undergo further critical appraisal and development within the DWAF project.

The DWAF project is designed to include a great deal more about the social and economic issues (see earlier comments in this section) and it is anticipated that these will then be better integrated with the Reserve and operating rules that have dominated this report.

9.6 Training and technology transfer

The software products generated by this project have been included in the SPATSIM system in which many other RDM related models and data analysis facilities already exist (Hughes, 2004a). There are already a number of SPATSIM users throughout South Africa and the IWR have arranged training sessions in the use of the software on several occasions. The SPATSIM system is also being used as the new platform for the revised water resources of South Africa database (WR2005) and is therefore expected to be used more widely in the future. SPATSIM is continually being updated and therefore is not distributed with this report. Anyone wishing to apply the software products referred to in this report can contact the IWR for an initial installation of SPATSIM, after which updates are readily available from the IWR web site (www.ru.ac.za/institutes/iwr and look for the link to 'Hydrological Models and Software').

Two separate training requirements can be identified. The first would be designed for the specialists who may be tasked with establishing the system for a specific water management authority, while the second would be designed for the personnel of the water management authority who would be tasked with running the real-time system operationally.

9.6.1 *Training in setting up the system*

This training would be directed at personnel who are already reasonably familiar with the application of rainfall-runoff models and system yield models. The focus of the recommendations for training is on the low flow component of the real-time operational system and additional training would be required for the high flow component. The training would focus on the following issues:

- Generating natural flow time series using a rainfall-runoff model and their importance with respect to triggering Reserve requirements.
- Identifying suitable real-time reporting rainfall measurement stations and the use of data from these in the re-calibration of the Pitman model.
- The basics of the SPATSIM framework, features, attributes, adding and editing data, running models from SPATSIM.
- The use of the SPATSIM version of the Pitman model and its similarity with the PITMAN2005 model.
- The water use data requirements of the real-time system, operating rules and their meaning.
- Setting up a water resources systems yield model to include all the water users and the Reserve.
- Optimising the systems yield model and the determination of the operating rules.
- Populating the real-time models with data.
- Testing the models to make sure that the information generated is appropriate for a specific water management area.

Depending upon the existing level of expertise and experience of the trainees, the training session would probably take between 3 and 5 days.

9.6.2 *Training in the use of the real-time operational system*

The amount of time required for training in the use of the low flow operational support system will be much less than for setting up the system. It is assumed that such training could be completed in approximately 1 to 2 days. The focus in this training would be on the use of the software and the interpretation of the results. The assumption is that the material being used for training would be directly relevant to the trainees, i.e. a system that has been set up for their specific water management area would be used. The focus would be on the following topics:

- Background to the approach, the Reserve and water user operating rules.
- Rainfall data collection and data entry.
- Checking the data and handling missing data.
- Generating the rainfall inputs to the rainfall-runoff model.
- Overview of the Reserve management model.
- Reserve management areas.
- Viewing the operating rules.
- Generating the operational results and interpretation of the drought severity graphs.
- Interpreting and acting on the decision support information.

10. REFERENCES

Conrad, J. (2005) *Preparation and production of a series of GIS-based maps to identify areas where groundwater contributes to baseflow* (WRC Project Number K5/1498). GEOSS Report No. G2005/02-1

DWAF (1994) Algoa Water Resources System Analysis: Systems Yield Analysis (PM 000/00/0993).

DWAF (2002) Algoa Water Supply Pre-Feasibility Study: Main Report (PM 000/00/2602), Hydrology and Systems Analysis of the Kouga System (PM 000/00/1902) and Water Supply Systems Analysis (PM 000/00/2302).

DWAF (2004a) Algoa System Annual (2004) Operating Analysis (PWMA 15/M00/00/0510).

DWAF (2004b) Guide to Electronic data – Reserve Determinations Study – Thukela River System. Department of Water Affairs and Forestry, Pretoria, South Africa Report No. PBV000-00-10316. Available on CD.

Hughes, DA (Ed) (2004a) *SPATSIM, an integrating framework for ecological Reserve determination and implementation*. Water Research Commission Report No. TT 245/04.

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

Hughes, DA and Mallory, SJL (2007) The importance of operating rules and assessments of beneficial use in water resource allocation involving multiple water use sectors. Submitted for publication, May 2007

Hughes, DA, O'Keeffe, J, Smakhtin, V and King, J (1997) Development of an operating rule model to simulate time series of reservoir releases for instream flow requirements. *Water SA* **23(1)**, 21-30.

Hughes, DA and Parsons, R (2005) Improved explicit ground water recharge and discharge simulation methods for the Pitman model – explanation and example applications. Paper presented at the *12th South African National Hydrology Symposium*, Midrand, Sept. 2005.

Hughes, DA and Smakhtin V (1996) Daily flow data time series patching or extension, a spatial interpolation approach based on flow duration curves. *Hydrol. Sci. Journ.* **41(6)**, 851-871.

Mallory, SJL (2005) The modelling of water restrictions applied in complex bulk water supply systems and the application of these techniques to operationalising the ecological Reserve. Paper presented at the *12th South African National Hydrology Symposium*, Midrand, Sept. 2005.

Smakhtin, VU (2000) ***Simple methods of hydrological data provision***. Water Research Commission Report No. 867/1/00.