SPATSIM, AN INTEGRATING FRAMEWORK FOR ECOLOGICAL RESERVE DETERMINATION AND IMPLEMENTATION
(K5/1160)

Incorporating Water Quality and Quantity
Components for Rivers

by

DA Hughes
(Editor)

The Institute for Water Research,
Rhodes University

Joint report to the Water Research Commission of the projects:

"Further development of methods to quantify water quality aspects of an ecological reserve assessment and dissemination of information decision support systems and associated manuals" ***K5/1312***

by

CG Palmer

and

"Development of hydrological procedures and tools to support the implementation of the water quantity component of the ecological reserve for rivers" ***(K8/510)***

by

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Many individuals and organisations have contributed to the information contained within this report and to the development of SPATSIM. The IWR have made use of SPATSIM in several ecological Reserve determinations and other water resource type studies for several years and during that time a number of comments and suggestions have been made that have contributed to the improvement of the system as a whole, or individual models associated with it.

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Dr Andy Young
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During the several courses that have been offered to date, the participants always managed to find something wrong with SPATSIM and the developers appreciated having these pointed out and being given the opportunity to correct the errors!

EXECUTIVE SUMMARY

This report represents one of the outputs of three Water Research Commission funded projects. The other outputs include the developed methods, tools and models, as well as the software associated with these. The three projects involved are:

K5/1160: The development of a computer based decision support system for quantifying the components of the ecological Reserve.

The objectives of this project were to develop a consistent protocol for the quantification and assessment of the ecological Reserve within a risk-based framework. Part of the objective was to design and program a software package that would accommodate all the steps and procedures required for quantifying the ecological Reserve. Emphasis was placed on the quantity component for rivers, although it was also intended to add tools to assist with other Reserve components where possible and appropriate. The development of a risk-based process for the assessment of the water quantity aspects of the ecological Reserve was to be based on combining biotic flow-stressor response relationships with flow time series.

K5/1312: Further developments of methods to quantify water quality aspects of an ecological Reserve assessment and dissemination via a DSS and associated manuals.

The two main objectives of this project were to further develop and refine the water quality Reserve methods and to integrate water quality data, tools, techniques and methods within the SPATSIM package.

K8/510: The development of hydrological procedures and tools to support the implementation of the water quantity component of the ecological Reserve for rivers.

The primary objective of the third project was to identify the requirements and limitations of DWAF for implementing ecological Reserve requirements and to develop procedures and tools necessary for implementation. A further objective was to train relevant DWAF staff in the use of the developed procedures.

The main reason for incorporating the final reports of these three projects into the same volume is that they all share a common thread in that the products have been incorporated as part of the SPATSIM software package.

SPATSIM

SPATSIM (Spatial and Time Series Information Modelling) has been developed at the Institute for Water Research (IWR) at Rhodes University with partial funding support from the Water Research Commission. The developments are still continuing (although at a slower pace) and the IWR has also invested many resources into the development. The long-term aim of developing SPATSIM was to replace all of the modelling, pre- and post-processing software that was contained within the IWRs DOS based HYMAS system (Hughes, et al., 1993 and 1994) and to add additional components that allow improved efficiency of data access and modelling. One of the primary motivations for the development was to integrate many of the ecological Reserve determination methods into a single integrated software package. Section 2 of this report provides a summary of the design principles of the software package and the facilities and tools that have been included in SPATSIM to date. The essence of the software design is to make use of a spatial interface to drive access to other data and to have a series of additional utilities that either use those data, or generate and store additional data. Some of the utilities are part of the main program, while others are external programs that are called from the main program. Example utilities include data importing routines, database management routines, model parameter estimation and editing routines, time series simulation models and graphical display programs. The software has been designed to be flexible, such that the number of possible add-on utilities is limitless and their implementation quick and efficient. This approach facilitates the development of new utilities by a range of contributors, rather than just the IWR. As the development of SPATSIM is highly dynamic (the IWR is currently adding a range of drought assessment routines funded by the International Water Management Institute, Sri Lanka) this report, or any printed user manual, will be out of date almost as soon as it is published. For that reason all the details of the various facilities are accessible through the software as 'help' information (see Section 2.5 for more detail), which is also available (and frequently updated) on the Institutes web site (http://ru.ac.za/institutes/iwr - see the link to Hydrological Models and Software).

SPATSIM is developed using the Delphi programming language and ERSI Map Objects. While the Institute for Water Research has no intention of marketing the software commercially, the use of Map Objects involves the payment of an application development license fee to ESRI for every version of the software that is distributed to users. The IWR therefore passes on the costs of this license fee (R1200 at 2004 prices) when distributing the software. The payment of this license fee and registration of a SPATSIM user allows future access to all updates which are regularly posted and available for downloading from the Institutes web page (see Section 8). The IWR staff also started a programme of training in the use of the software for various purposes during 2003. These courses are available on a commercial basis for groups of prospective users.

While much of the motivation for the development of SPATSIM was the need to integrate various data analysis tools and models to facilitate the determination of the ecological Reserve, it has also been used for a variety of other water resource assessment applications. The Institute has had a long history of involvement in the Southern Africa FRIEND (Flow Regimes from International Experimental and Network Data – a UNESCO IHP project), initially funded through the Water Research Commission. It is currently involved in several collaborative water resource assessment projects within the SADC region (sponsored by DFID and the European Union) where the rainfall-runoff modelling capabilities of SPATSIM are being applied, tested and improved (for example: Kafue River Basin, Zambia and the Okavango River Basin, Angola, Namibia and Botswana). Several cooperating partners within the SA FRIEND programme have also received training in SPATSIM and are using it within their own countries (Tanzania and Swaziland, for example).

The details of most of the models and data analysis procedures that are included in SPATSIM are not provided within this report. There are other sources of information (see the references section) that explain the background and theoretical concepts, while further details can be obtained from the software or web based help files.

National Reserve Database

The Desktop Reserve model has proved to be a very useful approach for rapidly generating Reserve information and has been used frequently (including all the Reserve information that is contained within WSAM – the South African Water Situation Assessment Model). However, there still remain doubts about the extent to which the model is able to generate estimates that are close to those that would be generated through more detailed assessments that fully utilise the available information on ecohydrological relationships. At the same time the information base upon which desktop type estimates can be made is expanding all the time as more intermediate and comprehensive Reserve studies are completed. Section 4 of this report explains the development and use of a SPATSIM application that has been setup specifically to capture the output from detailed Reserve determinations and make use of this information to refine the parameters of the Desktop model to try and improve the confidence that can be expressed in its results. Section 4 outlines the structure of the database that forms the core of the SPATSIM application, explains the procedures to be followed for adding new information for a Reserve determination, provides further details about running the Desktop model and includes a section that explains how the model parameters can be re-calibrated for specific regions or basins. The latter is facilitated by a SPATSIM 'model' (Desktop Parameter Calibration Model) that allows new Reserve determination results to be incorporated into the calibration procedure. This model can also be used to approximately assess the level of confidence that can be expected from applying either the national default set of parameters or a newly calibrated set.

The main outstanding issue is how to establish reliable procedures for continued population of the database as more determinations are undertaken by a wide group of DWAF Service Providers. It is also necessary to determine who, or which group, will manage the database and receive all the information. Logically, this should be the RDM Office of DWAF if they have the staff capacity to fulfill this function. There seems to be little doubt that the RDM Office should be the custodians of the database, even if they rely upon outside assistance to maintain it. The RDM Office has the responsibility for recommending Reserves to the Minister and therefore it is important that they have access to the most up-to-date information on a national basis. They are also faced with the task of extrapolating from past determinations to new sites and the Desktop calibration model is designed to assist with that process. One of the other issues to address is the methods that will be used to disseminate the information in the database to a wider audience to allow others to make use of the experience base that it contains. Clearly some type of web-based procedure would be ideal but it is not immediately apparent how best to achieve this. The main recommendation is that the RDM Office assume responsibility (either themselves, or through the appointment of a suitable agent) for ensuring that the database is up-to-date and make it the responsibility of all Reserve specialist teams to supply the necessary information at the conclusion of a determination. Guidelines on the required data and its format are provided within this document.

Flow-Stressor Response Method

Project K5/1160 also involved further development of the Flow-Stressor Response (FSR) approach to environmental flow requirement assessment and therefore the basic principles and application of the method are discussed in more detail within this report (see section 5). Section 5 also includes some illustrations of the use of the SPATSIM tools that are available to facilitate the application of the method. The FSR approach has been used in several Reserve determinations over the last few years and despite teething problems, it has proved to be a very efficient method when applied at the comprehensive level (i.e. an assessment based on field work and detailed data analysis of all components of a Reserve determination).

The final part of Section 5 refers to the criticisms often leveled at comprehensive Reserve determinations – the fact that they take a long time, require several specialists and cost a lot of money. The report suggests that the way forward could be related to the development of the Ecoregion Classification System and associated databases. The information that forms part of that system could be utilized and extended to include generic flow-stress relationships, as well as generic guidelines for determining stress regime characteristics under different levels of ecological functioning (associated with ecological categories A to D), to form the basis for a more rapid approach to the FSR method. While the development of such an approach would require further research and populating the classification system with additional data, it is suggested that the benefits in terms of more rapid Reserve determinations would offset the initial investment. There are also issues associated with the expected level of confidence that could be achieved, and those that would be required under the prescriptions of the National Water Act. This same section notes the fact that it has not been possible to develop an equivalent 'flow-stressor response' method for high flows, despite several attempts during various meetings and workshops. Although not viewed as a critical issue, as alternative methods are available and integration with the low flow approaches are not essential, it nevertheless remains a gap that could be filled in the future.

Water Quality Reserve Determination Methods

Integrating different kinds of information has allowed the development of an Environmental Water Quality approach to assessing the Environmental Water Requirements (Rivers; EWR: Rivers) for water quality. The information sources are the physico-chemical water quality data, biomonitoring data and ecotoxicological data and the links between these data types. Their use in an EWR:Rivers, is described. The methods presented in this report represent the most up to date record of methods currently available to describe the water quality aspects of an EWR: Rivers and are being incorporated into SPATSIM. A description of the steps necessary for the assessment of water quality is provided.

Unlike flow, water quality comprises several variables and the report deals with:

Selected inorganic salts:
- Sodium chloride, sodium sulphate, magnesium chloride, magnesium sulphate, calcium chloride, calcium sulphate.
- Salinity, measured as electrical conductivity to be used under specified circumstances.

Nutrients:
- Phosphates (PO_4^{-3}) and total inorganic nitrogen.

Physical variables:
- Turbidity.
- pH.
- Oxygen.
- Temperature (only in cases of thermal ecosystem impact).

There is provision for a requirement to test for selected complex industrial mixtures.

Response variables:
- SASS (aquatic invertebrates).
- Algal abundance
- Toxicity.

A start has been made on the SPATSIM facilities required to facilitate the determination of water quality in EWR:Rivers, however, some details are still outstanding and will be incorporated as they become available. Procedures for importing water quality time series data into SPATSIM are already in place and form the basis for a water quality data analysis model. This model allows the user to statistically summarise the data, display time series plots and Box and Whisker plots, as well as selecting the start and end dates for further analyses on the basis of trends in the data. The concentrations of the major salts are also estimated from the raw data. Some additional tools have been developed, such as the modeling of flow together with concentration so as to produce concentration time series, the use of these time series data in stressor response modelling and the creation of flow-concentration scenarios for the selection of ecological categories. The next stage of development should include the incorporation of these approaches into SPATSIM.

Reserve Implementation

The details of the work that was undertaken as part of project K8/510 on the implementation of the water quantity component of the Reserve for rivers are reported within Section 7 and further elaborated within the software or web based SPATSIM help information. This project attempted to identify the issues that were associated with implementation and specifically to identify the gaps in tools and explanations that inhibit the implementation of the Reserve in different circumstances. Some of these tools have now been developed and incorporated into SPATSIM, but it was also discovered that developments in implementation are lagging far behind the developments in Reserve determination. This has meant that it was not always very straightforward to obtain well-articulated answers to questions related to implementation problems. However, despite this it has become clear that the issues can be divided into those related to institutional management and perceptions of the provisions of the New Water Act, those related to monitoring and a wide range of technical issues associated with the transfer of information from the RDM Office of DWAF to the regional management staff and the use of that information by the staff. These technical issues can be quite different depending upon whether the system being managed is a relatively large-scale water resource development involving storage and the capacity to control flows, or whether it is a system of distributed small-scale abstractions. The former can be divided up into those situations where the high-flow component of the Reserve is to be managed (more difficult) and those where, for various reasons, it is not (much easier). One of the common technical issues is the provision of the natural hydrological 'trigger' or 'signal' which is used to quantify what level of Reserve flow is required at any specific time (this association between the Reserve requirement and the variation of natural flow is central to the way in which environmental flows are expected to be managed in South Africa). Part of Section 7 deals with this issue in detail and offers some critical discussion of the various alternatives. One of the alternatives for low-flow management is the near real-time updating of a monthly rainfall-runoff model based on a set of selected reporting raingauge stations. This would appear too offer a useful approach that is not too data intensive and can be applied at a regional scales without excessive staff resources (in terms of either numbers or expertise).

The report indicates that managing for high flow releases will always be relatively complex, despite the fact that many of the technical tools are already available within SPATSIM. Part of the complexity is associated with the need for a good forecast of what is about to happen in other parts of the catchment (especially downstream tributaries) in order to minimise artificial releases to achieve a specific downstream flow objective.

One of the tools that has been developed within SPATSIM is designed for the assessment of either existing abstractions, or license applications for new abstractions, in the context of available water and the Reserve. This is effectively the smaller scale equivalent of a yield model applied to larger systems. The water requirements of different users (which include stream flow reduction activities, small farm dam developments and direct river abstractions) are specified in a relatively simple way and the water balance model that accounts for the effects of these on the natural flow regime is very simple. The results are displayed as flow duration curves and are directly comparable with the assurance rule curves that are the standard output from all Reserve determination process.

General and Achievement of Objectives

There is no overall conclusion to this report as each section represents a separate study. While the terms of reference of the three projects have been addressed and most of the objectives have been met, there are still outstanding issues. Part of the reason for this is that the development of the procedures for determining and implementing the Reserve is a dynamic process that is far from complete. New issues are being raised all the time and there are many individuals and institutions that are only now beginning to understand the concepts and therefore possibly identify new problems. These projects have contributed many new ideas and tools to the whole Reserve process and during that time a number of individuals and organisations have been exposed to these ideas and trained in the use of the tools.

While the procedures and software for undertaking the low flow component of the flow-stressor response method of Reserve determinations have been fully developed, the same is not true of the high flow component. There appears to be no general consensus on the most useful approach to applying the stressor response principle to high flows. This is not a serious issue as alternatives are available which do work and have been used successfully.

One of the objectives of the second project was to integrate all the water quality tools into SPATSIM. However, there are still some technical details of those tools that have not been fully resolved. As soon as they have been resolved, it is a relatively simple matter to add the new components to the existing water quality data analysis routines that already exist within SPATSIM. This will be undertaken as part of the IWR commitment to the ongoing support of the SPATSIM system.

One of the objectives of the third project, was to train regional DWAF staff in the tools that have been developed to assist with implementation. However, it became apparent during the course of this 1-year project that many of the regional staff are not ready to receive such training and there is a need to establish the context of the Reserve at the level of regional water resource management first. There are DWAF projects currently in progress that are investigating the best methods of fitting RDM issues into the whole water allocation process. It is also clear that some of the SPATSIM approaches are appropriate to these emergent methods. It should therefore be easier to establish the training needs of regional water management staff in the near future and begin to introduce them to the tools that have been developed during this project.

Training in the use of SPATSIM continues, as does its development. It has already been proved to be a reliable and efficient platform for analysing a variety of water resource problems within South Africa, within SADC and elsewhere. The software has reached a level of development such that adding new facilities is relatively quick and straightforward (depending on the complexity of the facility to be added). This presents an ideal opportunity for the IWR to form partnerships with other organisations that require water resource assessment tools that have not yet been included. If such organisations can mobilise the funds required to cover the IWR costs of adding the tools, then all SPATSIM users benefit as these become available with the next appropriate update. There have been criticisms leveled at the WRC and organisations such as the IWR for promoting the development of modelling software within South Africa when many systems are already available from other countries with greater development resources. It is the contention of this report that a product such as SPATSIM that has been designed by local practitioners to directly address some of the water resource issues of South Africa and is understood and can be modified immediately by a locally based team at very low cost, represents a sound investment. SPATSIM can now grow and adapt to requirements identified by the local water resource community (as well as the international community if there is more widespread interest in its use). The Institute for Water Research is committed to supporting this growth, even in the absence of any major funding in the future. Further improvements and refinements can be supported by:

- IWR resources during routine use of the system for consultancy projects.
- Identification and correction of ‘bugs’ during commercial training sessions.
- Additions of new models, components and facilities required by other users and funded through ad hoc contracts.

It is clear therefore that most of the objectives of the three projects have been met and that a sound platform has been established for ensuring that those few remaining issues can be readily addressed in the future as part of the ongoing improvement and application of the SPATSIM package.

CAPACITY BUILDING REPORT

PROJECT K5/1160

This project has been involved in the development of methods, tools and software. During the course of the project, many of the developed products have been used in consultancy projects, as well as being demonstrated to a wide variety of interested parties. It is therefore quite difficult to isolate capacity building actions that were designed to be specifically part of this project and those which could be considered to be related to the project through the developed products. This report therefore includes all the activities that can be considered as capacity building.

Direct training in ecological Reserve methods and software:

Apart from several commercial (i.e. those where the participants have paid a commercial fee for attending) courses on SPATSIM that have been held, the IWR has also held several other courses specifically for training new entrants into the field of ecological Reserve determinations. Some of these have involved small groups, while others have involved individuals. The main single group that have been involved are the Department of Water Affairs and Forestry. Several members of the RDM Office and the Hydrology Division of DWAF attended a two-day SPATSIM course in Grahamstown during 2002, while Ms Thokozani Mbhele returned to Grahamstown during 2003 for more intensive training and practice with the software. As part of the Thukela Reserve determination project Ms Siphesile Shange, of Umgeni Water, partnered Prof Hughes on the hydrology components and learnt in detail how to apply SPATSIM and many of the Reserve tools, as well as participating fully in a real Reserve determination. Ms Shange has subsequently been included on several Reserve study proposals from the IWR.

Prof Hughes has also provided backup support via e-mail to several companies that are using the SATSIM software within consultancies.

Apart from SPATSIM, a number of individuals have also been exposed to, and trained in, the Flow-Stressor Response approach, either through participation in consultancy projects (such as the Thukela) or through attendance at specialist workshops that have been held to develop or explain the method.

Making information more readily available:

It has been the IWR policy to try and place documentation about the project and its products on the Institute's web site as soon as possible. The whole of the SPATSIM 'Help' system is on the web page and this includes a number of 'Road Map' type systems that explain many of the methods and the use of the various hydrological tools. This capacity building action is relevant to the other two associated projects (K8/510 and K5/1312) The two main parts of the web site relating to this project have been accessed more than 800 times over the last two years.

International capacity building:

There has been a certain amount of interest in the use of SPATSIM as a water resource assessment tool, specifically from within the southern Africa region through the FRIEND project (the WRC funded the initial involvement of Prof Hughes in this UNESCO initiative through an earlier project). Prof. Jonathan Matondo and one of his students at the University of Swaziland, Dr Simon Mkhandi (University of Dar es Salaam) and Dr Dominic Mazvimavi have all been trained in the use of SPATSIM, mainly as a platform for the application of the

Pitman model. While not directly associated with the aims and objectives of the project, these individuals have benefited from some of the developments funded by the project. As part of an EU project involving hydrological and water resource modelling of the Okavango basin, Drs Julie Wilk and Lotta Andersson of Linkoping University, Sweden have learnt how to use the SPATSIM system for the purposes of setting up and running hydrological models.

Prof Hughes has also contributed to the environmental flow requirement component of a taught MSc course in water resource management offered by the University of Zimbabwe and supported by the Dutch Government.

PROJECT K8/510

This project was primarily a 1-year consultancy to investigate and try and resolve some of the issues associated with implementation of the water quantity aspects of the ecological Reserve for rivers. The capacity building objectives of this project were mainly focussed on raising the awareness and improving the competency of DWAF staff in Reserve determinations. There has therefore been a substantial overlap between this project and K5/1160 and most of the capacity building aspects referred to under that project are equally relevant for K8/510.

In this project, it is also recognised that members of the IWR have had their capacity enhanced through dialogue with various regional DWAF staff who are at the forefront of Reserve implementation and are therefore more aware of some of the practical issues involved. It is the belief of the project team that both groups have benefited from the discussions that have been held during the course of the project. The IWR certainly has a better appreciation of the difficulties of implementation and should therefore be able to improve future designs of tools, while it is hoped that the regional DWAF staff have a better idea of what is needed and available for implementation.

As part of our involvement in this project we have initiated discussions with Mr Mushudu Murovhi (DWAF, Eastern Cape) about the possibility of undertaking an MSc programme in the development and testing of a regional water resource management system incorporating abstraction licensing information and the Reserve. Essentially this is the next logical step to follow after the development of some of the tools that were part of K8/510. There was not time, nor the opportunity, during this project to properly test and apply the tools.

PROJECT K5/1312

This project has contributed to capacity building through research projects and through involving trainees in ecological Reserve projects (consultancies). In addition, workshops to discuss method development for the water quality component of undertaking ecological Reserve assessments have included appropriate persons to ensure that these methods become widely used, tested, peer-reviewed and accepted by the scientific community.

Research

UCEWQ-IWR has a number of postgraduate research students whose research has made input to this WRC project:

- Samantha Browne (MSc)
- Andrew Slaughter (MSc) (Student bursar on this project, to complete in 2004)
- Nosiphiwo Ketse (MSc)

Water Quality Method development and Consulting projects

Table: Water quality methods workshop participants

Name	Organisation	Workshop 1	Workshop 2
Marius Claassen	Environmentek, CSIR	*	
Laura Foster	TIDASA	*	
Andrew Gordon	UCEWQ-IWR, RU	*	
Dana Grobler	RDM Directorate	*	
Kim Hodgson	Umgeni Water	*	
Sebastian Jooste	RQS, DWAF	*	*
Neels Kleynhans	RQS,DWAF	*	
Heather Malan	FRU, UCT	*	*
Nikite Muller	UCEWQ-IWR, RU	*	*
Jay O'Keeffe	IWR, RU	*	
Suzan Oelofse	DWAF WQM	*	
Tally Palmer	UCEWQ-IWR, RU	*	*
Harrison Pienaar	RDM, DWAF	*	
Nico Rossouw	Ninham Shand	*	*
Patsy Scherman	CES	*	*
Adhishri Singh	RDM, DWAF	*	
Retha Stassen	RDM, DWAF	*	
Christa Thirion	RQS, DWAF	*	
Martin van Veelen	BKS	*	
Jay Walmsley	Mzuri Consultants	*	
Barbara Weston	RDM, DWAF	*	
Tandiwe Zokufa	RQS, DWAF	*	

The table above lists the individuals (including project staff) who participated at workshops to agree on water quality methods to be used in ecological Reserve assessments. At Workshop 1, all water quality methods were discussed and agreed upon, while at Workshop 2, only methods specific to inorganic salts and conductivity were discussed.

The table below lists the trainees who have been involved in Environmental Water Requirement (Rivers) assessments for water quality:

Table: Trainees in water quality Reserve assessments.

Reserve Study	Trainee
Olifants River Study	Diks Madikizela (Unitra) Tobile Bokwe (Umgeni Water)
Breede River Study	Tandiwe Zokufu (RQS, DWAF) Malisela Papo (RQS, DWAF) Wagied Kamish (Ninham Shand)
Thukela River Study	Ntomoboxolo Valisa (UCEWQ-IWR) Malisela Papo (RQS, DWAF)

1. INTRODUCTION
DA Hughes

1.1 PROJECTS ASSOCIATED WITH THE REPORT

This report represents a summary and guide to the results of three Water Research Commission funded projects undertaken by the Institute for Water Research with the assistance of additional specialists from other organisations.

The first (K5/1160) was entitled 'The development of a computer based decision support system for quantifying the components of the ecological Reserve' and its overall aim was to develop a consistent protocol for the quantification and assessment of the ecological Reserve within a risk-based framework. Part of the objective was to design and program a software package (section 2) that would accommodate all the steps and procedures required for quantifying the Reserve (sections 3 and 4). It was recognised that the initial emphasis would be on the quantity component for rivers, although it was also intended to add tools to assist with other Reserve components where possible and appropriate.

A further objective was to develop a risk-based process for the assessment of the water quantity aspects of the ecological Reserve, by combining biotic flow-stressor response relationships with flow time series (section 5).

The second (K5/1312) was entitled ' Further development of methods to quantify water quality aspects of an ecological Reserve assessment, and dissemination via a DSS and associated manuals'. The overall aim of this project is reasonably self-explanatory, but one of the objectives was to incorporate the tools and an explanation of their use within the SPATSIM system. The main objective, however, was the technical integration of water quality data, tools, techniques and methodologies within an ecological Reserve Decision Support System (section 6 and Appendix A).

The third project (K8/510) was a one-year consultancy project (Ecological Reserve Implementation – Hydrology) to contribute to the development of hydrological procedures and tools to support the implementation of the water quantity component of the ecological Reserve for rivers (section 7). While the title emphasises the development of tools and procedures, the project was also designed to identify the main issues and constraints facing water resource managers in their efforts to implement the Reserve in terms of the Water Act of 1998. The primary objective was were to identify the requirements and limitations of DWAF for implementing ecological Reserve requirements and to develop procedures and tools necessary for implementation. A further objective was to train relevant DWAF staff in the use of the developed procedures.

Many of the tools and procedures that are referred to in this report will continue to be modified and improved in the future (section 8). It was therefore decided that the full details would not be included here but be available through links to the Institute for Water Research web site at Rhodes University (http://www.ru.ac.za/institutes/iwr - see the link to Hydrological Models and Software), as well as being distributed as part of the SPATSIM software package. This approach is designed to achieve the objectives of making available a baseline summary of the work that has been completed and a guide to its use, as well as ensuring that access to the most up-to-date information is readily available.

The core product of these projects is the SPATSIM software package, which incorporates a variety of hydrological and water resource estimation 'tools' within an information management system with a geographic information system (GIS) user interface. These 'tools' include relatively straightforward data manipulation facilities (import, export, editing, viewing, etc.), 'models' (tools that generate simulated information from observed information) and 'road maps' which provide guidance in the use of either the 'models' or groups of models that form a methodology. The term 'Decision Support System' or DSS is used very loosely in the water resource literature and frequently means different things to different people. In the context of this report DSS refers to the SPATSIM system as a whole in that the stored information, the facilities for managing this information, the models and the road maps can all be used to facilitate decision making in the general field of water resource management, and the determination of environmental flows and water quality requirements (the ecological Reserve as define in the National Water Act of 1998) in particular.

While every attempt has been made in the report to use the most recent Reserve and RDM (Resource Directed Measures) terminology, it should be recognised that there are many terms that have not been finalised and frequent changes to 'official' terminology have been made during the time that this report was being compiled.

The focus throughout this report is on the Reserve for rivers. However, many of the analysis routines and methods are also appropriate to the other components of the Reserve (ground water, wetlands and estuaries) and in fact have been used in such studies in the past. There is no reason why further developments to incorporate specific analysis methods related to the other components cannot be included at some time in the future. One of the main points that is emphasised is that SPATSIM has been demonstrated to be a useful integrating framework and that adding new models, data storage or analysis routines can be undertaken quickly and efficiently.

1.2 CONTRIBUTIONS TO THE REPORT

This report has been compiled by the editor on the basis of inputs from several individuals. The authors responsible for the different sections are identified within the section headings and should be acknowledged when making reference to specific parts of the report. The Acknowledgements section at the beginning of this report indicates that many other individuals and organisations have made substantial contributions to the outcomes of these projects.

1.3 STRUCTURE OF THE REPORT

The first part of the report (Sections 2 to 4) deals with the SPATSIM package, providing a summary of the design and information processing facilities that have been included, as well as further details of its use and a specific example associated with the storage of water quantity Reserve determination data for the whole of South Africa. The latter detail has been included as an illustration of the design of a SPATSIM application and the documentation of its use. There is no implied suggestion that the details of this application will not change in the future.

The second part of the report (Section 5) focuses on the Flow-Stressor Response approach to determining environmental flows in the context of the quantity component of the ecological Reserve for rivers in South Africa. The background to this approach is included here, as well as guidelines for the application of the method (with cross-references to some of the SPATSIM tools) for Reserve determinations and the evaluation of flow scenarios.

The third part of the report (Section 6) focuses on the water quality components of the Reserve and the recommendations that have been developed under project K5/1312. The water quality method development was conducted by a team and in conjunction with other WRC projects. The history of method development is provided in Palmer et al. (In Press), and additional details on water quality-quantity modelling have been reported by Malan and Day (2002).

The fourth part (Section 7) represents the hard-copy version of the final report on the Reserve Implementation consultancy project K8/510.

The final part of the report (Section 8) provides guidance on access to SPATSIM and the various tools, as well further information on expected future developments.

It should be pointed out that many of the techniques referred to in this report and the software products of the projects are under continual review. For further information and updates (on methods and software) readers are directed to the Institute for Water Research web site (http://www.ru.ac.za/institutes/iwr - see the link to Hydrological Models and Software).

2. SPATSIM SOFTWARE PACKAGE
DA Hughes and D Forsyth

SPATSIM is the acronym for Spatial and Time Series Information Modelling and the software represents an attempt to package a wide range of water resource related information management tools within an integrated environment. 'Information' in this context refers to spatial information (location of rivers, basin boundaries, gauge points, etc., etc.), as well data associated with spatial elements, where 'data' can refer to text, single values, 1- or 2-dimensional tables, graphics and time series. The latter are in some ways the type of information that makes water resource related information systems different from many others.

2.1 BACKGROUND AND DEVELOPMENT PRINCIPLES

SPATSIM has been developed at the Institute for Water Research (IWR) at Rhodes University with partial funding support from the Water Research Commission. The developments are still continuing (although at a slower pace) and the IWR has also invested many resources into the development. The long-term aim of developing SPATSIM was to replace all of the modelling, pre- and post-processing software that was contained within the IWRs DOS based HYMAS system (Hughes, et al., 1993 and 1994) and to add additional components that allow improved efficiency of data access and modelling. One of the primary motivations for the development was to integrate many of the ecological Reserve determination methods within the new software package. During 1999, the IWR became intensively involved in the whole Ecological Reserve process, actually setting Reserves and developing software to facilitate the quantification process at various resolutions. These developments led to a proposal to the WRC for a project designed to develop a more complete decision support system for quantifying the Reserve. As part of the Reserve determination process involves the use of simulated hydrological data, it made a great deal of sense to abandon any attempts to re-write the HYMAS system until such a time that the requirements for Reserve determinations had been defined. The models and time series processing, display and analysis programs could then become an integral part of a new system that would replace HYMAS as a generic model application system, as well as functioning as a decision support system for the determination of the Reserve. Looked at in another way, the Reserve DSS could be considered as an integral part of a much more flexible software package that can deal with a variety of water resource and hydrology related problems.

During September 1999, Prof. Hughes visited Dr Alan Gustard at the Centre for Water and Ecology (CEH, formerly the Institute of Hydrology) in the UK and was shown the recent developments being carried out on their 'Micro-Lowflows' software (now referred to as LowFlows 2000). These developments were very impressive and the basics of the data access design appeared to be very useful, flexible and relatively straightforward to implement. Some of the design philosophy explained below has been largely based on what was noted during this visit.

As SPATSIM has been developed, HTML file 'help' facilities have been added to provide users with guidance for specific processes and to provide readily accessible reminders of what to do when applying specific functions of the software. It should be noted that SPATSIM is under constant development, with new functions being added all the time, while others are improved. The basic structure, however, is now stable and unlikely to change, meaning that older versions can be applied in parallel with newer versions. Section 8 provides further details about obtaining access to the SPATSIM software and future updates

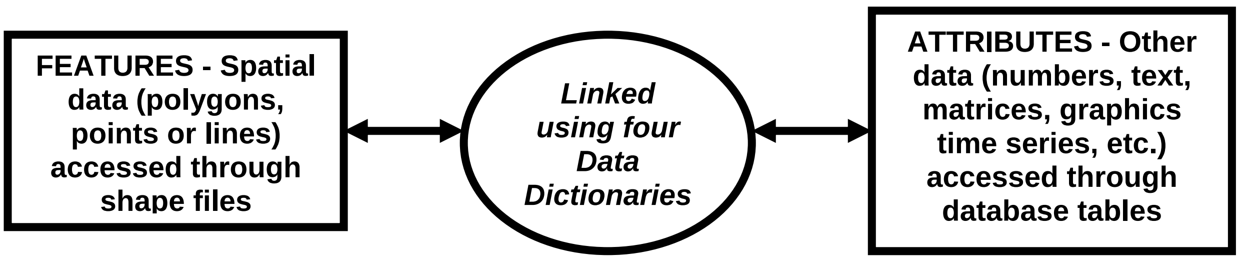
SPATSIM is being developed using Delphi and Paradox database tables (by default) with ERSI MapObjects to provide the spatial data analysis utilities.

2.2 DATABASE AND SPATIAL INTERFACE DESIGN

The essence of the software design is to make use of a spatial interface to drive access to other data and to have a series of additional utilities that either use those data, or generate and store additional data. Some of the utilities are part of the main program, while others are external programs that are called from the main program. Example utilities include data importing routines, database management routines, model parameter estimation and editing routines, time series simulation models and graphical display programs. The software has been designed to be flexible, such that the number of possible add-on utilities is limitless and their implementation quick and efficient. This approach facilitates the development of new utilities by a range of contributors, rather than just the IWR.

The design of the database access process forms the core of SPATSIM and is illustrated in Fig. 2.1. Spatial data (referred to as FEATURES) are accessed through shape files, while other data (referred to as ATTRIBUTES) associated with the spatial data are accessed through database tables (using Paradox tables by default). The links between the two data sources are controlled by a set of four data dictionary tables. Each application of SPATSIM is based upon a database alias name that contains a unique set of the four data dictionaries, as well as all the associated attribute tables. It is recommended that those users who are unfamiliar with the use of database alias' and tables for storing information consult a basis information technology or computer science textbook for an introduction to the concepts. The concepts are not dissimilar to spreadsheets where each 'sheet' represents a table, each column represents a field (or data type) and each row represents a record in the database (or a specific collection of values or information for each data type).

Figure 2.1 Basic data access design in SPATSIM



2.2.1 Spatial interface

The spatial interface is achieved through the use of MapObjects (ESRI) within a DELPHI program making use of Shape file coverages (generated through ARCINFO or any other appropriate GIS software), which have been digitised externally. Each of the coverages is identified as a ***feature,*** which will have ***attributes*** associated with the spatial elements (individual polygons, lines or points). While it is clearly possible to have data attributes defined as part of the shape files, SPATSIM stores these separately from the shape file tables within a database structure as defined below. The shape file coverages are therefore mainly used to define the ***features*** and the spatial characteristics of their elements. However, all of the shape files must have at least two internal attributes that are used to control access to the spatial data. These are the ID and Description fields of the shape file tables. The ID field has to be an integer data field that holds unique numeric reference numbers to all the spatial components that are part of the shape file. The Description field should contain alpha-numeric data that identifies the spatial components. The contents of the latter field play a major role in facilitating data import from other sources.

The main reason for adopting the above approach is that shape file tables are not readily capable of storing (as attributes) some types of data (such as time series). There is, however, no reason why attributes stored in existing shape file tables cannot be used within SPATSIM and some facilities have been developed for this purpose.

2.2.2 Main database structure

The shape file tables should have the general structure illustrated in Fig 2.2, the specific fields apart from the ID and Desc fields being dependent upon the coverage type (i.e. line, polygon or point) and whether or not additional attribute information has been included. The order of the fields in the database table is irrelevant. The IDField must contain unique integer numbers for each spatial element, while the DescField contains alpha-numeric descriptions of the spatial elements. These should also be unique for some of the data import routines of SPATSIM to function correctly. ***If these fields do not exist within a shape file that is to be used with SPATSIM, then they need to be added first (using appropriate GIS or database utility software).***

Figure 2.2 Shape file tables (*.dbf) used to define SPATSIM ***Features***

IDField	DescField	Other information (including spatial) depending on coverage type		

The **DATA DICTIONARY** of the SPATSIM database is made up of four components, the first being the list of ***features***. Fig. 2.3 illustrates the structure of the first component, which provides the link to the spatial data. The names given in the figure are the field names used in the Paradox database table (data_dict1.db) and their content is explained below. The number of records in data_dict1.db will be equal to the number of ***features*** that have been previously associated with a specific SPATSIM application.

- Feature Code: A unique number that is associated with a single shape file.
- Feature Name: The name of the ***feature*** for display and selection purposes.
- Feature Source: The path and filename of the shape file.
- IDField: The field in the shape table file that uniquely identifies a polygon, point or line.
- DescField: The field in the shape table file that the user selects as the main coverage attribute (i.e. part of the shape file definition) that is to be used to describe the cover component (for example, the quaternary catchment name in a WR90 polygon coverage).

Figure 2.3 DATA DICTIONARY Component 1

Feature Code	Feature Name	Feature Source	IDField	DescField

The second component of the data dictionary uniquely associates SPATSIM (i.e. not part of the shape file) ***attributes*** with a feature defined in data dictionary 1. The names given in Fig. 2.4 are the field names used in the Paradox database table (data_dict2.db) and their content is explained below. The number of records in data_dict2.db will be equivalent to the sum of all ***attribute*** references that have been added to the shape files referred to in data_dict1.db. There may or may not be data stored in the system for these attributes and if there is there may be data associated with one or more spatial elements. Note that each individual ***attribute*** is uniquely associated with a specific ***feature***.

- Feature Code: A unique number associated with a feature (shape file) contained within data dictionary 1.
- Attribute Name: The name of the SPATSIM attribute.
- Feature Code: A unique number associated with the attribute.
- Datatype: The type of data associated with the attribute that also defines the type of table that the attribute data will be stored in:

  0 = Text Simple text string with a limit of 80 characters.
  1 = Integer Single integer number value.
  2 = Real Single real number value.
  3 = T/S A set of values that represent a time series of data.
  4 = Bitmap A graphic image or movie clip.
  5 = Array A matrix of values representing a single attribute (not time series).
  6 = Memo A text document or similar set of strings.
  7 = Linked A link to an attribute associated with a different feature.

Figure 2.4 DATA DICTIONARY Component 2

Feature Code	Attribute Name	Attribute Code	Datatype

The third component of the data dictionary provides the link between the list of attributes and the database tables in which the data are stored (Fig. 2.5). The names given in the figure are the field names used in the Paradox database table (data_dict3.db) and their content is explained below. The number of records in data_dict3.db depend upon whether some data have been added for each individual attribute or not. The maximum number of records is therefore the same as data_dict2.db, while the minimum could be zero (i.e. no data added yet).

- Attribute Code: The link to data dictionary 2.
- Table Code: A unique code to identify the table in which the data are stored.
- Database Alias: The alias name (which also specifies the path and type) of the database in which the data are stored.
- Table Name: The name of the table in which the data resides which must have a structure (number and type definition of fields) that is compatible with the Datatype from component 2.
- Max. Rec: The maximum record number in the table defined by Table Name. This is stored here so that when additional data are added it is straightforward to increment the Table Record of data dictionary 4.

Although the IWR concentrate on the use of Paradox database tables, there is no reason why other database table types cannot be accessed. However, if new tables are created within SPATSIM, they will be Paradox tables. It should be apparent that all the data associated with a single attribute will be stored in the same table. It is also possible to store all data of a single type, but associated with many different attributes, within the same database table (see Section 2.2.3).

Figure 2.5 DATA DICTIONARY component 3

Attribute Code	Table Code	Database Alias	Table Name	Max. Rec

The fourth component of the data dictionary links the Table Codes from data dictionary 3 with the records in the spatial database (using the contents of the shape file IDField as specified in data dictionary 1) and the records in the database table associated with the Table Code (see Section 2.2.3). The names given in Fig. 2.6 are the field names used in the Paradox database table (data_dict4.db) and their content is explained below. The number of records in data_dict4.db will depend upon the number of spatial elements in a shape file, the number of attributes associated with each shape file and whether or not data has been loaded for each individual spatial element/attribute combination. For example, assume that a SPATSIM application has been established with the WR90 quaternary catchment coverage (1946 polygons) and attributes of MAR, MAP and catchment area. There will be 1946 * 3 = 5838 records in data_dict4 if the MAR, MAP and catchment area attributes have been populated for all polygons. Assume a point coverage of some DWAF streamflow gauging sites (say 80 point locations) is added, together with attributes for observed mean daily flow, catchment area and gauge identification number. If 50% of these points are populated for all three attributes the number of records will increase by 3 * 80 * 0.5 = 120.

- Attribute Code: The reference to the attribute defined in data dictionaries 2 and 3.
- Spatial Record: The number in the IDField of the table associated with the shape file referred to in data dictionary 1.
- Table Record: The number in the RECID field of the table associated with Attribute Code in data dictionary 4. The implications of this structure is that all the data associated with a single attribute has to be stored in the same database table. However, data for different attributes of the same type can be stored in the same, or different database tables.

Figure 2.6 DATA DICTIONARY component 4

Attribute Code	Spatial Record	Table Record

2.2.3 Attribute Database Tables

The remainder of the database structure is made up of as many tables as necessary containing the attribute data. Eight table types have been identified as required to store the different types of data commonly used in a variety of water resource related problems.

These correspond to the definitions given by the ***Datatype*** field in component 1 of the data dictionary. Figs. 2.7 to 2.15 illustrate the structure of the different tables, which all have a common field (RECID) corresponding to the value of the Table Record field of data dictionary 4. The attribute tables are created as they are required and can have any name specified by the user.

Figure 2.7 Text type tables. Made up of a simple structure of two fields. The Text field has a limited size of 80 characters.

RECID	Text

Figure 2.8 Integer type tables. Made up of a simple structure of two fields. The Value field can only store integer values (signed 4 byte integer numbers).

RECID	Value

Figure 2.9 Real type tables. Made up a simple structure of two fields. The Value field can store real (floating point) values.

RECID	Value

Figure 2.10 T/S type tables. Made up of a RECID field, several time series attribute fields (start and end date, units, data formats, etc.) and a binary large object (BLOB forming the Data field) containing the time series data as either data values or as pairs of time and data values (defined within the attribute fields).

RECID	Time series attribute fields												Data

Time series attribute fields:

GeogID: Up to 80 character description of the location of the time series data.
DataID: Up to 80 character description of the type of data stored.
Area: Catchment area (real number) if required.
Data Obj.: Data object type (integer) of the time series data (0 = fixed interval, data only; 1=variable interval, data pairs of time and variable).
Time Units: Units of time data (integer); 1=minutes; 2=hours; 3=days; 4=months; 5=years.
Time Int.: Time interval (integer) when the data object type = 0.
Time Int. Type: Time interval type (integer) when the data object type = 1. 0=steps or intervals; 1=cumulative time from year 1800; 2=cumulative time from year 1900. The cumulative times are assumed to be in decimal days.

Var. Type: Variable type of the time series data (integer). e.g. 1=length, 2=area and 3=volume data.
Var. Unit: Variable units type of the time series data (integer). E.g. if Var. Type = 3, the options are 1=litres, 2=m^3, 3=Ml, 4=$m^3 * 10^6$, etc.
MD Code: The code to be used to recognise missing data (real number).
Scale: A field that can be used to scale the data to ensure that it corresponds to the units specified in Var. Unit (real number).
Start Date: Start date of the time series data (Date field).
Start Time: Start time of the time series data (Time field).
End Date: End date of the time series data (Date field).
End Time: End time of the time series data (Time field).
No. Records: Number of records in the time series data (long integer).

Table 2.1 provides an explanation of the meanings of the various numeric codes for the Var. Type and Var. Unit fields.

Table 2.1 Variable type and unit codes

Variable	Variable Unit Types							
Type	1	2	3	4	5	6	7	8
1: Length	mm	cm	M	km	ins	ft	miles	
2: Area	m^2	hectares	km^2	Ft^2	$miles^2$			
3: Volume	litres	m^3	Ml	Mm^3	ft^3	gallons	Mill.galls	
4: Fluxes	mm/h	m/s	M/h	m/day	ft/s			
5: Rates	litres/s	m^3/s	M^3/d	ml/d	Mm^3/d	ft^3/s	gall/d	
6: Time	minutes	hours	days	months	years			
7: Weight	mg	gm	Kg	tonnes	cwt	tons		
8: Concs.	mg/l	gm/l	Kg/m^3	tonnes/m^3	cwt/ft^3	cwt/gal	tons/ft^3	tons/gal
9: Other	%	Fraction	mS/m	Stress				

Figure 2.11 Graphic type tables. Made up of a RECID field, several bitmap attributes (such as title, x and y sizes, date and source type - jpg, bmp, etc.) and a binary large object containing the graphic image.

RECID	Title	Xsize	Ysize	Date	Type	Graphic

Bitmap attribute fields:

Title: Up to 80 characters describing the graphic image.
Xsize: The horizontal size of the image in screen pixels (integer).
Ysize: The vertical size of the image in screen pixels (integer).
Date: The date that the image was created or loaded (date field), for information only.
Type: The type code of the graphic image (integer). At present 10 possible types are recognised (codes 0 to 9 = bmp, cgm, jpg, pcx, tif, gif, wmf, mpg, avi, mov).

Figure 2.12 Array type tables (or data matrices). Made up of a RECID field, several array attributes (such as title, date, format, etc.) and a binary large object containing the array data. This table type is used to store model parameter values or tables of data.

RECID	Title	Date	Rows	Columns	Format	Data

Array attribute fields:

Title: Up to 80 characters describing the data.
Date: Date of creation of the data (date field).
Rows: Number of rows in the data matrix or array (integer).
Columns: Number of columns in the data matrix or array (integer).
Format: File name containing the structure of the data in the matrix (80 character path and name of the format file).

Users can create their own format files (there is an option within SPATSIM to do this) as they are simple text file definitions of the data that will be stored within the Data field BLOB. An example of a format file (all such files having an extension of 'txp') is provided in Fig. 2.13. This data matrix consists of 12 rows (one for each month) and 7 columns representing model parameters. The fourth line in the file is used to allow for the later inclusion of default values (0 means that no default values are available). Within the Data field BLOB, the data are stored (and therefore should be accessed) in the order of row1/col1, row2/col1….row1/col2, row2/col2…etc. (i.e. by column first, then by row).

Figure 2.13 Illustration of the format of a TXP array definition text file.

```
Monthly Distributions for the Desktop Reserve model
12 Rows = Oct to Sep
7 Columns = Requirement components
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Baseflow %
High flow factors
Low Flow DC Shape
DC Upper % Shift
DC Lower % Shift
DC Low Flow Max.
High Flow DC Shape
```

Figure 2.14 Memo type tables. Made up of a RECID field, memo attributes (Title – 80 characters and Date – date field) and a formatted Memo field containing the text memo. This type of table could be used for storing notes about some of the data contained within other attributes or groups of attributes. For example, descriptions of the quality of data for flow gauging stations could be stored in a memo.

RECID	Title	Date	Memo

Figure 2.15 Link type tables. Made up of a RECID field and attributes that allow a link to be made to an attribute associated with a different feature. This type of table could be used for associating a time series already established for one point (gauging station for example) with a polygon or another point in a totally different coverage.

RECID	Feature	Attribute	Type	Sp. Record

Link attribute fields:

Feature: The source feature code (data dictionary 1) of the data (integer).
Attribute: The source attribute code (data dictionaries 2 to 4) of the data (integer).
Type: The attribute type code for checking purposes (integer).
Sp. Record: The spatial record number (in the IDField of the shape file and referenced in data dictionary 4) of the data source point or polygon (long integer).

Link attributes are used to avoid duplicating time series data across several features. Many of the external model processes work with the attributes of a single feature, while available information is often associated with more than one feature. An example would be a WR90 quaternary catchment feature, a gauged streamflow point feature and a feature of Reserve determination points. The Reserve points feature may be the one used with various models associated with the Reserve but it would be wasteful of space to duplicate the storage of the monthly and daily time series data associated with the other two features. Link attributes could therefore be made within the Reserve points feature that provide associations with time series data stored for specific polygons and points in the other two features.

2.2.4 Starting a New SPATSIM Application

The SPATSIM install CD will establish one or more example applications of SPATSIM, as well as registering the associated database alias' and the ESRI Map Objects database components. However, to create a new application it will be necessary to establish a separate database alias for the attribute database tables. The startup screen of SPATSIM allows the user to do this by prompting for the required information:

Database Name
Main Directory for the application
Shape File Directory for storing spatial coverages (Shape Files)
Raw Data Directory for storing text file information

The information is stored in a INI file that provides access to the correct directories and sub-directories every time the user runs this SPATSIM application. There are three additional actions required. The first is to locate the PROC_RUN.db, .mb and .px database files in an existing application and copy these across to the database directory (datab_dir in Figure 2.16) of the new application. These are the databse tables that store the details of any external model applications that have, or will be, established. The first time a new external model is established for the new application, the old entries in this table can be deleted. The final action is to edit the default label size (see Figure 2.16) to a value that is suitable for the scaling used on all the spatial coverages (dependent on the map units used and the size of the map).

A new application of SPATSIM will have no features or attributes associated with it at first and it will be necessary to use the 'Add Features' > 'New' menu item to locate the required shape files for inclusion. Once a feature has been added the 'Attributes' > 'Add' menu item can be used to establish the names of new attributes (this can also be achieved by double clicking on the list of attributes once one has been added). Note that the attributes are listed in alphabetical order and therefore it is good practice to use attribute names that will be grouped together in the list in some logical order. Adding attributes at this stage merely creates an empty attribute reference in data dictionary 2 and does not populate the database with any information.

Figure 2.16 Contents of a typical *.INI file for a SPATSIM application

```
[startup]
cover_dir=c:\thukela\cover
graph_bin=c:\tsoft\source
datab_dir=c:\thukela\dbdata
datab_name=THUKELA
label=0.05
doc_dir=c:\spatsim\docs
[Process]
exe_dir=c:\spatsim\source
rqo_dir=c:\spatsim\text_data
dat_dir=c:\spatsim\data
```

2.3 INTERNAL SPATSIM FACILITIES AND COMPONENTS

These parts of the software package are those that are accessed directly through the main SPATSIM program and have been coded by the main developers at the IWR. Others (see Section 2.4) are referred to as external utilities and can be added by the IWR or collaborating developers without having to make changes to the main SPATSIM system code.

This part of the document merely provides the user with basic guidelines to the availability of the various facilities and is not a 'user manual'. Users will note that the number and range of options is constantly changing as the software undergoes further development. Online help is available which is updated more frequently than this document and all potential users are encouraged to attend a SPATSIM training course to enable them to become familiar with the approaches used and the available facilities.

2.3.1 HELP facilities within SPATSIM

There are some basic help facilities that have been written in Delphi help and can be accessed by pressing F1 while some of the visual components of the software are active. However, this type of help is very limited and most of the help has been written in HTML file format and is available through the 'Help' menu option. These files are also available via the IWR web site (http://ru.ac.za/insititutes/iwr and look for the Hydrological Models and Software link and then the link to SPATSIM). If required, individual users may therefore modify their own versions of the help files. However, note that when updates are downloaded these modifications could be over-written unless the filenames and associated hyperlinks are changed.

At the time of writing this report the following sub-options were available via the SPATSIM help facility (use either '*Help -> Main Index'* and select from the left side of the screen in the web browser, or use '*Help -> Decision Support*' and select the required topic directly):

SPATSIM HELP:

Explanations of the database structure and the use of the various menu options within SPATSIM. This is the real 'help' and can be referred to for problems and or reminders of what to do in specific circumstances.

SPATSIM Models:

This help component provides a list and brief explanation of the various external models that have been currently included with the SPATSIM package. The details of the models are not provided, although in some cases hyperlinks have been made to scientific papers or reports that discuss the models and their applications. The main content of this help facility is to explain the input and output information requirements of the models so that users can obtain a better understanding of how to establish a model run through a SPATSIM application (the source of the input information and the destination of the output information).

Hydrology & the Reserve:

This is a 'Road Map' to the use of hydrological data within a water quantity Reserve determination for rivers. The main screen provides a diagrammatic DSS to the use of the various hydrological models and analysis techniques that can be used within a Reserve determination depending on the type and quality of data that are available. The menu items on the left of the screen provide hyperlinks to further details and guidance.

National Reserve Database:

The IWR and DWAF (Hydrology Division and RDM Directorate) have established a SPATSIM application for storing the results of all Reserve determinations in South Africa. This application also contains the default parameter values of the Desktop Reserve model for all the quaternary catchments in the country, as well as a facility for undertaking a regional re-calibration of these parameters based on detailed Reserve determinations at a number of points within the region. This hyperlink provides access to the most recent version of the manual for the use of this SPATSIM application. The current version of this manual is included in this report under Section 4.

Water Quality Reserve:

This section of the help provides a detailed 'Raod Map' and explanation of the recommended procedures to be followed for the determination of the water quality Reserve. A summary of this information is provided in Section 6 of this report.

Reserve Implementation:

This section provides a 'Road Map' of the issues associated with implementation of the Reserve, monitoring and compliance control. At the time of writing this report, many of these issues have still not been clarified and it is likely that substantial changes will still be made to implementation approaches in the future. The current situation and some of the solutions offered as part of SPATSIM are summarised in Section 7 of this report.

The '*RDM Manual*' option accesses a Delphi program that displays the flow diagram of the processes involved in the determination of the ecological Reserve. Clicking on parts of the diagram allow either pdf (Adobe Acrobat) or text files to be displayed that explain those parts of the process in some detail. The '*Viewer*' option allows the user to select which file viewing option to use. The '*RDM Manual*' option refers to the pdf files that are the main chapters of the official Department of Water Affairs reference manual on the Reserve (most current version at the time of writing this report), while the '*Appendices*' option accesses pdf files of the appendices to the manual. The '*Text Help*' option accesses text files that have been created specifically to provide guidance on the use of SPATSIM in the Reserve determination process.

2.3.2 Map or Feature manipulation facilities

The first menu item ('Features') refers to a number of facilities that allow features to be added, removed, printed or modified. In addition the first six menu icons are used to move around or label features.

Features -> Add menu item

There are two options associated with this menu – *Existing* and *New*. Choosing the *Existing* option allows the user to select a feature that is already referenced in the Data Dictionary, deciding on a colour to use for the display and then displaying it as the current feature. All of the attributes already associated with this feature will be listed in the attribute display list box.

Choosing the *New* option brings up a file select dialogue that allows the user to select a shape file from an available folder. When adding new features, it is important to check that the scaling units that were used to create the coverage are the same as those used for features that already form part of the SPATSIM application. When a new shape file has been selected, the internal data fields of the shape file table are identified and displayed. The user then needs to associate two of these with the SPATSIM requirement for an ID Field and a Desc. Field. Simply highlight the required shape file field and click on the relevant button. The result of the selection is summarised at the top of the selection window. Note that the ID Field will now be fixed (as references to the data in this field are used in the data dictionaries), while the Desc. Field can be changed later. Clicking on the 'Finished' button allows the user to specify the colour, the feature is added to the Data Dictionary and becomes the current feature with no associated attributes.

Features -> Remove menu item

There are two options associated with this menu – *From View* and *From Dictionary*. Choosing the *From View* simply deletes the reference to the current feature from the list of available Features and removes it from the map display. Removing a feature '*From Dictionary'* deletes the reference to the current feature and all associated attributes from the SPATSIM application. All the associated data stored in the SPATSIM database tables will be removed.

Features -> Change Colour menu item

This menu item is used to change the colours that are used to display the features and associated labels. It can also be used to display polygons as filled or transparent.

Features -> ID and Desc. Fields menu item

There are three options associated with this menu item. The *Edit Fields* option allows the user to change the shape file data attribute that is used as the Description Field for identifying spatial components. The current selection, as well as the list of available fields are listed. A new Desc Field can be selected by highlighting a suitable available field and clicking '*Finished*''. The '*Edit Info.*' Option allows the data in the shape file Desc. Field to be edited and saved. The contents of this field are used for labeling the spatial elements and therefore it is quite a simple matter to check the results of your editing. The '*Copy Desc. to Attr.*' option requires that a Text type attribute is currently selected (i.e. highlighted in the attribute list), so that the contents of the Desc. Field in the shape file can be written to a SPATSIM attribute database table. This is a simple method of transferring text type information from a shape file to an Attribute.

Features -> Point Features menu item

There are three options associated with this menu item. The *'Add Points'* option is used to add points in a point coverage and the coordinates given in the bottom right of the main screen are provided to assist with the location of new points. Selecting this option allows the user to enter a description and then click on the map to add the point. If the process is to be aborted, simply click the '*Abandon*' option on the small description entry box before clicking on the map. The *'Move Points'* option allows the user to click on a point on the map and then click on a new location to move the point. The '*Delete Points*' option isolates the current feature and allows the user to identify and select the points that should be removed. After the delete is performed, the user is returned to the main map and is required to re-select the colour used to display the specific feature.

Features -> Output menu item

There are two options associated with this menu item. The first, *'To File'* allows the current map view to be saved to either a bitmap (BMP) type graphics file, or to an extended metafile (EMF) type file. The second option (*'To Printer'*) simply uses the default map print command to print the current view to the default printer and is only really useful for getting a rough hard copy.

First Six Icon Buttons

The first icon button ('*Zoom Map*') is used to zoom in on the map view by clicking on the map and dragging in any direction.

The second icon button (*'Pan Map'*) is used to pan within an expanded map view (although the map view slide bars can also be used for this purpose. The map is clicked and the mouse dragged to move around in the full map.

The third icon button (*'Zoom Full Extent'*) allows the map to be re-drawn at its full size.

The fourth icon button (*'Show Labels'*) displays (or removes the displayed labels) the contents of the shape file 'Desc. Field' for all the spatial elements of the currently selected Feature.

The fifth icon button (*'Reduce Label Size'*) reduces the size of the displayed labels for the currently selected Feature.

The sixth icon button (*'Increase Label Size'*) increases the size of the displayed labels for the currently selected Feature.

2.3.3 Attribute manipulation facilities

There are a number of facilities that deal with the attribute data, where they are stored, how they are imported and edited, how to display them, etc. This section refers mainly to the second main menu item ('Attribute') as well as icon buttons number 9 to 11.

Attribute -> Add menu item

This facility is for adding empty Attributes to the data dictionaries. The user is prompted for an Attribute name and to select the data type. A new attribute reference is created in data dictionary 2, but no data, or database table references are added to data dictionary 3 until data are added to the attribute using one of the other utilities. Double clicking on the attribute list box (when there are existing attributes) achieves the same objective of allowing a further attribute to be added to the current feature.

Attribute -> Delete menu item

This facility allows attributes and all associated data to be removed from the current application of SPATSIM.

Attribute -> Rename menu item

This facility simple allows the name of the currently selected attribute to be changed.

Attribute -> Add Array Template menu item

This allows a new array definition text file to be created by specifying the name of the format, the number of rows and columns and the descriptions of these rows and columns.

Attribute -> Where are Data menu item

This can be used to identify spatial elements that have data associated with them for the current attribute. Up to 10 spatial elements are 'flashed' in sequence and the user prompted to continue or abandon the search. This facility can be useful if only a few points or polygons have data already loaded and the user has forgotten which they are.

Attribute -> Import or Edit menu item

There are 6 options associated with this menu item. The '*From Tables*' option allows data to be imported from existing database tables which have fields that are compatible with the fields of the database table associated with the current Attribute. It is also necessary for the database table representing the source of the data to have a field, which is compatible with a field in the shape file table that will be used to uniquely relate the importing data to a spatial element. The user is therefore expected to identify the '*Feature Key Field*' (click on the list of available Feature Fields). The user then gets the required database table and then identifies the '*Source Data Key Field*' (highlight the required field in the list of source data fields and then click the '*Set Key Field*' button). The source fields associated with each of the Attribute destination fields can now be established by clicking on the required row of the transformation table, clicking on the required source data field and then clicking the '*Add Source Field*' button. Any data type can be imported but the source and destination field types must be the same (they can both be BLOBs, for example). It is also possible to set a constant entry into one of the destination fields by typing the value or text into the table (in which case the source type becomes 'User'). Clicking the '*Save Data*' button will then search for matches between the source data and feature key fields and where these are found will copy the specified source fields into the relevant fields of the Attribute database table.

The '*Add/Edit Arrays*' option is a multi-function array editing facility that can also be accessed from the table icon (button no. 10). The user can select one or more (only more than 1, if the array is a single dimension) spatial elements and the stored data will be displayed once the '*Add/Edit Arrays*' button at the bottom of the list of selected items is clicked. The data can now be manually edited by moving around inside the table. It is also possible to copy selected rows from one column to another (highlight the rows to be copied and specify the From and To columns and then click '*Copy*'). Rows and columns can also be scaled by constant values (make sure that the correct row or column is selected in the table first). Data can also be imported into the array from a text file where three options are available. The first two are flat ascii files with a single number per line and no header lines or titles. If the first option is selected ('*Rows First*') then the data must appear in the file as row1, col1; row1, col2; etc., while the opposite applies for the '*Columns First*' option (i.e. row1, col1; row2, col1; etc.). For the third option ('*Table File*') the data appear in the text file in exactly the same format as in the table displayed on the screen (i.e. 'n' columns of values per line and 'm' rows or lines of data). Two further utilities are provided; '*Print Arrays*' to output the data to a printer and '*Write to File*' to export the data to a text file (with the option to invert the array first). The final two buttons are for saving the data after editing and for returning to the main SPATSIM screen (does not automatically save the results of the edits and is therefore equivalent to abandoning the edits).

The '*Text Tables to Array*' option is for importing from text files into arrays associated with many spatial elements on the basis of the Desc. Field entries in the shape file table. The first entry in a block of text in the importing data file should be the alpha-numeric string that is equivalent to a Desc. Field entry in the shape file. The rest of the first line of each data block contains the data for the first column of the array, each value being separated by at least one space). The next lines of a data block contain the data for the remaining columns of the array (if the array has more than a single column), but without the alpha-numeric identification. There are then as many data blocks as required, each one representing the array data for a single spatial element. If a match between the alpha-numeric string and a Desc. Field entry in the shape file table is not found then the data are ignored.

The '*Text to Tables*' option is similar to the previous option, but applies only to importing single integer or real values. The text file is then much simpler and contains lines of data with the alpha-numeric string to identify the correct spatial element and the data value of the currently selected Attribute.

The '*Import T/S*' option allows access to a generic time series import facility that caters for a wide range of different raw data formats. Data can be imported into multiple spatial elements using either the names of the imported files or a station name entry within the file (either as a header line or as part of each line). The exact form of the different file options varies, as does the degree of user control over the import process. All users are expected to familiarise themselves with the various code values used to determine the type of variable and the units of the imported data (see the SPATSIM help options an variables and units). This facility provides a relatively quick and flexible approach to importing time series data into SPATSIM Attributes.

The '*From Feature Attribute*' option is used to transfer data contained within a shape file table to a SPATSIM attribute. The available attributes of a shape file are listed and the user simply highlights one for selection. When the '*Add Attribute Data*' button is clicked, new values are written to the currently selected SPATSIM Attribute from the selected feature attribute of the shape file. This is only used for single value numeric data (integers or real numbers).

Attribute -> Intersect menu item

This utility is provided to allow new attribute data to be generated for selected spatial elements of a polygon feature based on the values for a shape file attribute of another polygon coverage. The first step in the process is to select the polygons that will have data generated for them using the '*Identify Upstream Elements*' icon (icon button no. 8), for which the currently selected attribute should be of text type and contain the Desc. Field entry for the next spatial element downstream. Once the icon has been clicked, the user clicks on the most downstream spatial element of the catchment or basin and all upstream elements are automatically selected.

Before starting the intersection process it is necessary to highlight the SPATSIM attribute that will receive the results (rather than the downstream catchment attribute that was used to select the catchments). This attribute can be a single real value or an array type. If an array type is selected then it will be necessary to specify the row and column of the array that is to receive the intersection results data.

The next step is to select the feature and its internal (shape file) attribute that is to be used as the source of data for the intersection process. This attribute should contain numerical data (either integer or real). Once the shape file attribute has been selected it is possible for the user to enter a transformation matrix, given that the attribute values contain no more than 20 unique values (i.e. they are index values, rather than true measurements of some variable – an example would be an index of vegetation type, rather than a true measurement of leaf area index). When the intersect process is started, the destination SPATSIM attribute data is generated as an area weighted sum of all the transformed attribute values of the polygons in the source feature that intersects each of the selected destination polygons.

This process can be used to generate distributed catchment rainfall-runoff model parameters from a range of shape files that contain raw catchment characteristics (such as coverages of soil, vegetation, geology, etc.). It is possible to generate several different parameter values using the same coverage by modifying the transformation matrix.

Attribute -> Link Attribute menu item

This menu item is designed to allow a linked attribute to be established so that the data associated with spatial elements in one feature can be referenced by the spatial elements in a different feature without repeating the storage of the data. The procedure starts with the feature and attribute combination where the destination of the link is to be stored. With the destination feature and attribute highlighted, click on the spatial element that the data are to be linked to. Then change to the source feature and attribute and click on the spatial feature that contains the source of the data. Clicking the '*Save Link*' button completes the process if the source data are available. Note that before the destination spatial element can be clicked, the 'Select Spatial Element' icon button (no. 7) must be in the 'down' position.

Attribute -> Render menu item

This menu item has three options and has been included to allow a polygon feature to be rendered (shaded) using classes based on single integer or real attribute values, or the value of a single row/column combination of an array attribute. The first option ('*Set Array Element*') is used to set the row and column combination if the selected attribute is an array type.

The second option ('*Start*') initiates the rendering process and moves to the render key page. The user may now set the number of categories, as well as the maximum and minimum data values for continuous data (real numbers). In the case of integer values (discrete rendering) individual colours are selected for each class, while for continuous rendering the upper and lower colours are set and the gradation is determine automatically.

The final option (‘*Remove*’) clears the current rendering and, strictly, this should be done between each new rendering (to avoid memory errors).

Show Attribute Data Icon (Icon button 11)

This is a generic attribute data display utility that applies to all data types except the Array type (it has its own set of displaying utilities). With the exception of time series data, this facility can be used to add, as well as edit, new information for a specific spatial element. This is achieved by either simply editing numbers or text data, or in the case of the bitmap data type, by loading information from an existing file. In the case of time series data, some of the details of the data series (such as data units, data time intervals, etc.) can be modified, but the time series data cannot be modified.

If time series data need to be modified then they can be output to a file (part of this menu item), edited and then re-imported (using the Import T/S option of the menu item Import or Edit). The output to file option allows for a limited number of data conversions before the data are finally written to file. Daily data can be converted to monthly volumes, while monthly volumes can be converted to monthly mean flows. The final format of the output files is in ‘spreadsheet’ format with three header lines. ‘Spreadsheet’ format for monthly data consists of lines with a four-digit year followed by 12 monthly values and an annual total (the first month is October). For daily data each line consists of a four-digit year, the month and then 28, 29, 30 or 31 flow values. In both cases the assumption is that all values are separated by a least one space and written with a precision of three decimal places. Files with this data format can be readily imported back into SPATSIM.

2.3.4 Data Exchange facilities

Data Exchange -> Export menu item

The ‘*Export*’ facility allows SPATSIM users to create exchange database tables to send to others users who can use the Import facility to add the data to their database. The procedure is as follows:

- Highlight the feature and attribute associated with the data to be exported.
- Click on the '*Exchange Data -> Export*' menu option.
- This will display a blank list of spatial elements.
- The '*Select Spatial Element*' icon button will be activated.
- Click on all the spatial elements that you wish to export data for and when all elements have been selected, click on the '*Export Data*' button.

The export facility creates an Export text file, which is located in the 'Export' sub-directory (see the ini file 'exp_dir=' line), as well as database tables in the dbdata sub-directory for any attribute type that has been selected for export. These tables are called by the following standard names:

Text data	= 'exp_text'
Integer data	= 'exp_int';
Real Data	= 'exp_real';
Time Series Data	= 'exp_ts';
Graphics Data	= 'exp_graph';
Array Data	= 'exp_array';

Memo Data = 'exp_memo';

Note that Linked attribute data cannot be exported.

One set of data is exported at a time (i.e. a single Feature/Attribute combination), but several sets can be added to the Export text file before sending the results to another user. To distribute the data, copy the '*Export.txt*' file and all the '*exp_???.**' files from the dbdata sub-directory. The receiving user places these files in their equivalent sub-directories and uses the '*Exchange Data -> Import*' menu option to retrieve the data.

Data Exchange -> Import menu item

To import data from another SPATSIM application, ensure that the relevant '*Export.txt*' file is located in the 'Export' sub-directory (see the ini file 'exp_dir=' line) and that the '*exp_???.**' database table files are in the database sub-directory. Clicking the '*Exchange Data -> Import*' menu option will begin scrolling through the available data to import, showing the name of the feature and attribute associated with the data. The user then ensures that the destination feature and attribute are correctly selected and clicks on the 'Go' button to begin importing those data. An import Feature/Attribute combination can be skipped over by clicking the 'Skip' button. The import facility follows the following steps:

- The names of the spatial components (Desc. Field) that have been exported are read.
- The same names are sought in the Desc. Field of the Feature of the destination application.
- The data are then added to the database table associated with the selected Attribute.
- If a record for that spatial component already exists it is over-written, while if a record does not exist, the database table is appended to.
- If no data currently exist for that Attribute, the user is prompted to supply a new or existing database and table name.

It should be clear that the receiving feature must have spatial elements, which have the same names (in the Desc. Field of the shape file table) as the sending feature. Therefore two users can only really share data if they have the same basic shape file information and do not make independent changes to the contents of the Desc. Fields.

2.3.5 Data Generation Procedures

These are included as an integral part of SPATSIM as they are common data manipulation procedures related to hydrological and water resources time series data.

Generate Duration Curves

Generating flow duration curves from time series data is a frequent requirement within hydrological and water resource applications. Before making use of this facility, ensure that there is a time series type attribute that contains data for the spatial element of interest and that an array type attribute has been created to receive the generated duration curve data. If the array type attribute has never had data added to it, the user will be prompted during the data generation procedure for the format of the array (using a .txp file). The correct array format file to select is '*durc.txp*'.

The procedure is started by ensuring that the appropriate time series attribute is highlighted and then selecting the '*Procedure -> Generate DC's*' menu item. It is then necessary to click on the '*Select Spatial Element*' icon before spatial elements can be selected. Any number of spatial elements can then be selected, after which the destination attribute (an array type) for the duration curves is highlighted and the '*Select DC Attribute*' button clicked. To start the calculations and save the results click the '*Generate DC's*' button. It is at this point that a .txp file and destination database table will have to be selected if the DC attribute does not already contain data.

Transform Time Series facility

This facility is provided to allow users to generate new time series from an existing one using a relatively simple transformation equation. The facility allows for two types of transformation equation, each with three parameters and also allows for two sets of parameters to be applied, one below and one above a specified threshold value of the original time series. It should be noted that the transformed time series are written back to the same attribute. If the original data are not to be lost a new attribute should be created and the time series copied to that first.

Spatial interpolation facility

A frequently required facility for hydrological and water resource modelling is the need to interpolate from point data to generate areal averages (converting point rainfall data to catchment rainfall data, for example). A procedure has been developed that allows point data to be spatially interpolated to area data using an inverse distance weighting method plus an additional weighting using gridded mean monthly data. This is accessed form the '*Procedure -> Point to Area*' menu item. The first step in the procedure is to select the polygons of a feature that are to be included in the analysis. For this to work, it is essential to have a text attribute that is used to identify the downstream relationships between polygons. The attribute data are simply the contents of the Feature Desc. Field for the next downstream polygon.

Having clicked on the '*Procedure > Point to Area*' option, click on the '*Identify Upstream Elements*' button and then click on the most downstream polygon to be used in the analysis. All the upstream polygons will be coloured in blue and the list of selected polygons displayed. Now click the '*Select Spatial Element*' button and click once at the centre of a circle and then drag to draw a circle that will represent the maximum search distance to use for all the polygons. This is the maximum distance that any polygon will look for points to be used in the spatial interpolation process. Click on the 'Start Interpolation' button to begin the analysis.

SPATSIM will now move to the Spatial Interpolation page and the user is required to enter the details of the data that will be used.

Interpolation Period

- Set the start and end dates of the final interpolated data, bearing in mind that if no point data values exist for any points within the search radius for part of that time, then mean values will be substituted.
- Set the time step for the interpolated data (fixed at either daily or monthly).

Destination and Source Data

- Select the destination of the interpolated data by clicking on the required Feature (must be a polygon feature) and the Attribute (must be a time series attribute) within the two lists on the right of the screen.
- Select the source data for interpolation, which must be a point feature and a time series attribute. The interpolation is carried out using an inverse distance squared

weighting procedure such that closer points to the polygon have a greater influence on the interpolated result.

Weighting Data Sources

- It is also possible to apply an additional weighting, by using a gridded coverage of such as median monthly rainfalls. This is used to improve the weighting procedure in areas where there are few source points so that some areas are not very well represented. The gridded weighting data are then used to avoid systematic errors in the interpolation procedure. Four weighting data sources are allowed for as all the gridded data may not be in a single coverage and the destination polygons could overlap up to four grid features.
- The feature should be a point coverage and the attribute selected should be an array (matrix) type with 12 monthly values.
- The additional weighting procedure then estimates the mean of all the grid points within a specific polygon (for the relevant calendar month in the time series) and multiplies the first estimate of a single gauges contribution (based on the inverse distance squared method) by the ratio of this mean to the grid value at the gauge.

Search Radius and Max. Search Items

- The search radius (in map units) is calculated from the first part of the process, but can be modified here if necessary.
- The 'maximum search items' refers to the maximum number of points that will be used in the interpolation process. If fewer items are available within the maximum search radius then only they will be used.

Interpolate and Finished Buttons

- Click on the '*Interpolate*' button to begin the process and then the '*Finished*' button to return to the main map screen.

View PDF File Option

If a path and filename to a PDF file (Acrobat file) is entered into a text type attribute this facility can be used to view the information. This is a useful method of adding references to detailed reports in the SPATSIM database. Ensure that the appropriate text attribute is current and click on a spatial element that contains the PDF file reference.

Median Rainfall Option

This facility has been added to allow the extraction of information in the correct format from a single file (GRIDOUT.ASC) of monthly median and annual rainfalls for all the 1' * 1' grids covering South Africa. This single file is very large and attempting to import data from it can be very time consuming. The user simply specifies the upper left and lower right hand corners of the block to be extracted and a file name for the results. Monthly data (which includes annual) can be extracted, or just the annual value.

These data can then be imported into an appropriate attribute (Array type with 1 column and 13 rows for monthly data, single real value for annual) associated with one or more point features containing a point for each 1' * 1' grid (these are available from the IWR or can be constructed through ARCVIEW or similar GIS software). The 'Text Tables to Array' option would be used for the monthly data, while 'Text to Tables' would be used for the annual data. Note that the Desc Field in the shape file must contain the decimal longitude and latitude values in the same format that is written to the text file. A short extract from one text file is provided below for illustration:

32.00S21.07E   181.0
32.00S21.08E   199.0
32.00S21.10E   206.0

The monthly median rainfall data can be used in the procedure to generate areal average rainfall data from point rainfall data time series. The gridded median monthly values provide part of the weighting procedure.

Sub-Quat. MAR Option

One of the problems frequently experienced in Desktop or Rapid Reserve determinations is the need to scale quaternary level streamflow data to a point on the river that is within the quaternary catchment. Simple catchment area based scaling, frequently does not work very well due to the spatial variations in rainfall and runoff response. A simple approach has been tested by the IWR to provide a better estimate of the scaling factor. It is based on a weighting using the ratio of the mean annual rainfalls over the sub-quaternary area to the total quaternary area. The approach is not totally satisfactory but does appear to generate improvements in results (Hughes, 2004b). The estimation equation used is effectively a correction to a catchment area based scaling of the quaternary catchment MAR using the ratio of MAPs:

MAR Ratio = Area Ratio * (3.4347 * MAP Ratio – 2.2989)

A database table (SPATSIM/DBDATA/SA_GRID.db) has been included in the SPATSIM alias.. This table contains all the design flood parameters for a 1' * 1' grid covering the whole of South Africa which were developed by Prof. Jeff Smithers of the School of Bioresources and Environmental Hydrology at the University of Natal, Pietermaritzburg under a WRC funded project. One field of this table is the mean annual precipitation.

Selecting the 'Procedure' -> 'Sub-Quat. MAR' option and then clicking on a point at the outlet of the sub-quaternary catchment activates the list box and button at the bottom right of the map and displays the quaternary catchment in which the sub-quaternary area lies. Click on all the points that are required to approximately define the boundary of the sub-quaternary area (these will be progressively displayed as black squares). When the boundary is finished, click on the 'Select Sub-Quat. Pts' button to activate the analysis screen and the click on the 'Calculate' button to access the database and calculate the following, based on the grid points that lie within the quaternary catchment and the sub-quaternary area:

- MAP of the quaternary catchment.
- MAP of the sub-quaternary area.
- Ratio of the two MAPs (sub-quat / quat).
- Ratio of the two areas (sub-quat / quat).
- Estimate of the ratio of mean annual runoffs (MAR sub-quat / MAR quat) based on the approach given in Hughes (2004b).

2.4 EXTERNAL APPLICATIONS

Under this main heading there are two principle options; '*T/S Graphs*' and '*Run Process*' which are accessed through the '*Applications*' main menu. The former refers to accessing the generalised time series graph display and analysis program (TSOFT – see Hughes et al., 2000), while the latter refers to running a wide variety of external application programs (models, etc.) that use the SPATSIM database information. Both of these menu sub-items have additional options to run an external application directly (i.e. run one that has already been established), or to establish a new external application after selecting spatial elements and attributes.

2.4.1 Generalised time series graph display and analysis facility

A software package (TSOFT) was already partially developed, before work on SPATSIM was started. The data access in TSOFT works with a 'profile' (a reference file to sources of time series data) of different time series that may be stored in several different ways. It was relatively simple to generate a link from SPATSIM to TSOFT, whereby a profile is created (or added to) by selecting spatial items for a time series type attribute. An external call to TSOFT (passing the profile name) completes the process. One advantage is that once the profile has been generated the TSOFT facilities can be accessed independently of SPATSIM (assuming that the location and database record numbers of the required data are not changed) and data from other sources added to it (i.e. not part of a SPATSIM database).

TSOFT can be accessed directly, in which case the required profile is selected by the user, or the '*Select First'* option can be used to identify Attribute/Spatial Element combinations that are to be added to a new or existing profile (identified using a standard Windows file dialogue). In the latter case, the '*Select Spatial Elements*' icon button has to be clicked into a down position, after which the user is able to highlight Attributes and click on spatial elements until the list is complete.

The facilities that are allowed for within TSOFT are described more fully within Water Research Commission Report No. 867/2/00 (Hughes et al., 2000) and include a wide variety of time series display and analysis routines that are frequently used within water resource analysis projects, including Reserve determinations.

2.4.2 Model running facilities

To facilitate linking a wide variety of external models and other time series analysis programs to SPATSIM, without having to re-code the main program, a generic facility has been established for calling external programs. All models will have different data requirements and therefore one of the facilities required within SPATSIM is to be able to associate data sources (through attributes) to model requirements. This has been achieved through the use of '*model requirement files*' (simple text files with an 'req' extension) and an example for the Pitman monthly rainfall-runoff model is given below (comments have been added to explain some of the contents):

Three lines of explanation

Pitman Model Requirements 'Title for display in SPATSIM'
1st parameter 0:Required, 1:Optional
2nd parameter=Table Type (-9:Multiple Var. File, 99: Other File)

Two lines specifying the external program name to call from SPATSIM
1. EXE File
0 99 mpit.exe

Two lines defining the source information for the structure of a temporary output file

2. Output Requirement File
0 99 Pitman.rqo

Two lines defining the name of a temporary multiple variable output file (not used now)

3. Model Results Data (T/S)
0 –9

Pairs of lines for each model requirement. The first line defines the name of the requirement, while the second line indicates whether it is a strict requirement (0), or an optional requirement (1) and what type of SPATSIM attribute it refers to (for example, 2=real type, 3=time series type and 5=array type). See section 2.2.2 for a full list of attribute types.

4. Catchment Area
0 2
5. Catchment Model Parameters
0 5
6. Optimisation Ranges
1 5
7. Reservoir Model Parameters
1 5
8. Mean Monthly Evaporation
0 5
9. Mean Monthly Distribution Data
0 5
10. Reservoir Monthly Distributions
1 5
11. Catchment Average Rainfall (T/S)
0 3
12. Catchment Average PE (T/S)
1 3
13. Upstream Inflow (T/S)
1 3
14. Transfer Inflow (T/S)
1 3
15. Downstream Reserve Requirements (T/S)
1 3
16. Downstream Outflow (T/S)
1 3
17. Reservoir Storage (T/S)
1 3
18. Observed Monthly Flows (T/S)
1 3

The '*Application -> Help*' option lists all the currently available applications and double clicking on one of these displays the attribute requirements for running the application (as listed above for the example of the Pitman model). This option can therefore be used to help in the preparation of a specific external application.

If the '*Application -> Select First*' option is chosen, the user is first prompted to select the spatial components that will be modelled. This may be a single point or polygon, or a set of points or polygons (i.e. a group of sub-catchments making up a complete basin). The exact procedures for spatial selection depend on the model and whether the '*Select Spatial Element*', '*Identify Upstream Elements*' or '*Identify Downstream Elements*' icon should be clicked down. In general terms the first is used where single or un-related groups of spatial elements are involved, the second for distributed sub-catchment type models such as rainfall-runoff models and the third where the downstream sequence of catchments or points is important (as in the Residual Flow Diagrams Generation Model).

The user is then prompted with the list of model requirements and is expected to either enter a filename (as in the model results data – item 3 in the example above) or highlight an attribute and double click on the model requirement to link the SPATSIM data (as input or output) to the model requirements. Some of the requirements are necessary for the model to run, while others are optional (either optional inputs or outputs generated by the model).

The third part of the process before running the model is to save the requirements, which is achieved using a single table (proc_run) in the application database for all external model applications. The structure of this table is given below, together with an explanation of the various fields of the table:

Description	Date	EXE	RQO	Data Dir	Output File	Feature	Spatial Elements	Attributes

Continued:

Output Var List	Attribute List	Spatial Input List	Spatial Link List	Spatial Output List	Start Date	End Date

Description: 40 character description of the modelling application
Date: Date that the application was created (or edited) as a date field.
EXE: Name of the external application to run from SPATSIM (64 characters).
RQO: Name of the file containing the output specifications file (64 characters). This only applies to rainfall-runoff models which store some of the state variables in temporary binary files.
Data Dir: Directory for the temporary output data file (64 characters).
Output File: Name of the temporary output data file (20 characters). This file is used in some models to store multiple variables (according to the specifications given by the RQO file) that the user may not require written back to the SPATSIM databases, but may be useful for such as model calibration or results analysis. These files can be accessed by TSOFT to display the detail of the model results if necessary.
Feature: The feature to be used to access attributes and data tables.
Spatial Elements: The number of spatial elements to be included in the modelling application.
Attributes: The number of model attribute requirements.
Output Var List: Yes/No codes for the output variables that are to be included in the temporary output file (where applicable).
Attribute List: Attribute codes of the model requirements.
Spatial Input List: ID numbers for the spatial elements associated with the input data. These would be the sub-catchments in a semi-distributed model and can involve more than are to be actually modelled (see next field).
Spatial Link List: The order and downstream-upstream linking associations for the input spatial components. The linking (where it is required) is carried out when the user selects the spatial components and relies upon having an attribute that defines the links. Some of the spatial components may be excluded.

Spatial Output List: Yes/No codes for the spatial elements that will have/not have output data written to the temporary output file.
Start Date: Model start date (date field).
End Date: Model end date (date field).

The structure of this table has been specifically designed for semi-distributed time series simulation models and many of the fields are not used for other external processes and applications.

Any model program code that is associated with SPATSIM needs interface procedures that are used to read a record in the '*Proc_Run'* table and interpret the information in the various fields to be able to access the SPATSIM databases through one or more of the data dictionaries. The rest of the model code can be developed totally independent of SPATSIM. Any model can then be run from SPATSIM as an external process, or independently without SPATSIM being loaded at all. Guidance is available from the IWR for any organisation wishing to add a model or external application to SPATSIM (this has already been successfully achieved with two independent groups).

Selecting the '*Application -> Directly*' option allows the user to pick the application and then run the program directly (without setting up a new application). The user is then required to select the specific application manually from the list in the 'Proc_Run' database table. If an application is selected that is not compatible with the selected external program, an error message will result.

The following external applications have been incorporated at the time of writing this report, while an update and further details can be obtained from the SPATSIM help or the IWR web site.

General hydrology data analysis models

Baseflow Separation Calibration Model: A process that uses an attribute of baseflow separation parameters to generate a time series of baseflows that separated from total flows through a digital filtering method (see Hughes et al., 2003).

Patching Model (Flow Data): A streamflow time series data patching and extension model that is based on the used of flow duration curves to extrapolate data from one or more sites to another (see Hughes and Smakhtin, 1996).

Patching Model (Using Rainfall Data): A streamflow data generation model based on the same concepts as the previous model but based on source data that is generated from records of rainfall using an antecedent precipitation decay function to convert discrete daily rainfall data into a more-or-less continuous rainfall index time series (see Smakhtin, 2000).

Tributary Inflow Analysis Model: A model that assesses the contribution of gauged or simulated tributary inflow time series to the streamflow in the main channel over a range of main-stream flood events. This model has been developed to assist in the determination of releases from upstream control reservoirs to meet flood and fresh event environmental flow objectives downstream, given possible tributary inflow contributions.

Residual Flow Diagrams Generation Model: A model to illustrate the downstream patterns of natural flow compared with present day flows and Reserve requirements.

Catchment Rainfall-Runoff Models

Pitman Monthly Model: A semi-distributed monthly time-step rainfall-runoff model that incorporates a large-scale reservoir water balance model at the outlet of each sub-catchment (if required), as well as the specification of instream flow requirement (IFR) releases from the reservoir. The model can be operated through an automatic optimizer for some of the rainfall-runoff model parameters, or through simple manual calibration (editing the parameters through normal SPATSIM procedures).

Pitman Monthly Model with revised ground water routines: This is a new version of the Pitman model that is currently being developed and uses a modified parameter set for the main Pitman model. The additional ground water routines include more explicit representations of recharge and ground water discharge, while a channel routing attenuation function has also been added for use in large catchments. Further developments are expected during 2003 to add channel margin loss, sub-surface drainage (to downstream sub-catchments) and a simple ground water abstraction routines (Hughes, 2004a – a copy of this paper is available through the SPATSIM help).

VTI Model: A semi-distributed daily time-step rainfall-runoff model that also incorporates a large-scale reservoir water balance model and IFR releases. As the model parameter estimation procedures can be quite complex, the application incorporates a parameter editing procedure.

Flood Models

Design Flood Model: A semi-distributed design flood model that can use both the Rational Mthod and the Nash-Muskingum Routing models to generate design floods from design rainfall data for different return periods.

Water Resource System Models

Rapid Simulation Model: A simplified systems yield model developed by Stephen Mallory and incorporated into SPATSIM with assistance from the IWR through WRC funding.

Ecological Reserve Models

Reserve Method DSS: A procedure for analysing the site specific situation and data availability (in a nominal manner) for the range of specialisations involved in river ecological Reserve determinations and indicating which Reserve determination method will be the most appropriate to use. It is based on the generation of a cost-confidence matrix from the answers to a set of fixed questions. It also includes an allowance for the protocols related to the type of planned water resource development and the need for confident estimates.

Present Day Hydrological Class: A model for analysing the duration curves of natural and present day streamflow time series and assigning a present day ecological class based on the differences between them (this model is not really used now and is about to be replaced by a more comprehensive eco-status evaluation model).

Desktop Reserve Model: The low-confidence regional parameter based model for estimating water quantity Reserve requirements for rivers based on monthly streamflow data. The time series output of Reserve requirements from this model can be used as input to the Pitman model (Hughes and Münster, 2000; Hughes and Hannart, 2003).

Desktop Parameter Calibration Model: A procedure for investigating the stored results of all water quantity for rivers Reserve determinations and assessing the parameter values of the Desktop Reserve model (see Section 4 of this report).

Daily IFR Design Model: A daily model to take the output of a BBM based Reserve determination process, calibrate the operating rules and generate a time series of daily Reserve requirements. The time series output of Reserve requirements from this model can be used as input to the VTI model.

Stress/Flow & Risk Indicator Model: A set of procedures to support the Flow-Stressor approach to determining the low flow ecological Reserve (water quantity for rivers) requirements. Outputs from the Pitman, VTI and Patching model are appropriate for generating time series scenario inputs to this process, as are outputs from the Desktop Reserve and Daily IFR Design models (see Section 5 of this report).

Flood Stress/Event Model: The equivalent of the above model for high flows (currently under development but not fully tested and evaluated).

Reserve Licensing Model linked to the Desktop Model: A model designed to make use of some of the outputs of the Desktop Reserve model, time series of natural and present day monthly flows, as well as some simple water use parameters to evaluate present day and likely future water abstractions in the context of the Reserve requirements. It is viewed as a tool that may be of value to regional water resource managers in evaluating applications for water use abstractions (see Section 7 of this report).

Water Quality Data Analysis Model: A model to facilitate the evaluation of water quality data in the process of setting the water quality Reserve (see Section 6 of this report).

This document is not designed to provide guidance on the use and application of all the various external processes. Many of them are documented elsewhere (see references), while others require specialised training before they can be successfully applied (Daily VTI model, for example). The later sections of this report do, however, provide some more detail of those models that have been developed specifically within the groups of projects directly associated with this report.

2.5 SPATSIM HELP, ROAD MAPS AND DECISION SUPPORT

This report represents a summary of the current status of the SPATSIM software package and facilities, while the HELP facility within SPATSIM provides more complete and up-to-date information. The majority of the HELP information has been prepared as HTML files which are also accessible from the IWRs web site at http://www.ru.ac.za/institutes/IWR (through the Hydrological Models and Software then SPATSIM link. All of these HTML files are supplied with a typical SPATSIM installation and can be edited by individual users if necessary. The main reason for wanting to do this would be to modify the help information to better suit an individual user (i.e. change some of the explanatory text or add new help in response to verbal or e-mail contact with the developers). Both the web site and package help files are updated periodically as new facilities are added to the software. The new help files are accessible through the web based update facility, together with any code changes to the software.

There are six main components to the main HELP facility:

- SPATSIM Help, consisting of general help and information on the package and its main facilities. This component should be accessed for 'how to' information.
- SPATSIM models, containing brief explanations of all the external models that are currently accessible from SPATSIM. Each model description contains information on the model input and output requirements that should be consulted before making use of the model for the first time. This information should assist a user in checking that

the correct attributes are available and (if necessary) populated with the correct data before an attempt is made to set-up a model for running.

- Hydrology and the Reserve. This help component starts with a road map explaining the process of using hydrological data within a Reserve determination process. Additional help is available on various issues related to the hydrological component of the Reserve including some information on the use of the Flow-Stress Response method (see Section 5 of this report).
- National Reserve Database. This help component is equivalent to Section 4 of this report and has been prepared to assist users in the application of this specific SPATSIM application.
- Water Quality Reserve. This help component is a more complete version of the guidelines for the application of the water quality component of the Reserve (see Section 6 of this report).
- Reserve Implementation. This is a 'Road Map' help facility to provide information on many of the issues relating to implementation of the Reserve, which were compiled as part of a WRC consultancy project (K8/510). Many of these issues are still largely unresolved due to the lack of Reserves that have been implemented. More details on these issues and the current status of implementation are provided in Section 7 of this report.

It should be noted that SPATSIM has been developed with limited resources and the development of a comprehensive help system for this type of software package involves a great deal of time and effort. While many of the basic functions of the software are fairly comprehensively covered there are other areas that are dealt with in less detail. For example, there are no detailed help facilities that will guide a first time user through the use of some of the more complex models that are included. It has been assumed that users will have access to other sources (their own experience, original model user manuals or a specialized course) for learning how to use such models. What SPATSIM provides is a common platform for the application of such models, which should make it easier to access and apply them.

2.6 SPATSIM - GENERAL CONCLUSIONS

In the context of the Reserve, the main objective of developing SPATSIM was to create a platform for applying a wide range of tools and models, storing and retrieving data and information in an efficient manner, as well as incorporating help and guidance in the use of the various approaches to Reserve determinations. One of the motivations for this objective was to provide the basis for a more consistent approach to Reserve determinations. There can be little doubt that a trained user of the SPATSIM system can undertake a Reserve determination in an efficient and consistent manner. However, it should always be remembered that successful Reserve determinations are based on inputs from specialists who understand the scientific basis for the relationships between biotic functioning and flow regime modifications. SPATSIM merely provides the specialists with a range of tools, which can be used to apply their specialist knowledge in a consistent framework.

The Reserve determination process can be based on different levels of data analysis and interpretation ranging from the very quick and low confidence desktop approach, through rapid and intermediate type determinations to a comprehensive study. One of the advantages of using SPATSIM and its associated models and tools is that the basic methodology is the same regardless of the level of determination. Some of the tools (such as the stress/flow and risk indicator model) may not be used in the less detailed determinations, but the final outputs and principles remain the same for all methods.

SPATSIM has only recently been used by Reserve determination teams that are not closely associated with the IWR. It remains to be seen whether or not the type of training that is currently offered (see section 8 and the Capacity Building section of this report) is sufficient to allow new teams of specialists to apply the software with relative ease, or whether the IWR will have to re-think its training and deployment strategy in the future.

3. SPATSIM AS A WATER RESOURCE ASSESSMENT TOOL
DA Hughes

While a great deal of the initial motivation for the development of SPATSIM was related to providing a platform for access to and application of Reserve determination tools, it was also associated with the need to replace the out-of-date HYMAS system developed within the IWR during the early 1990s for DOS operating systems (Hughes et al., 1994). HYMAS was developed as an integrated system for the application of rainfall-runoff and water resource assessment models and many of the HYMAS models have been carried across to the SPATSIM system.

The basis for any water resource assessment study is the ability to manage all available data in a consistent and efficient manner, to be able to view and summarise those data and to be able to use those data to generate new information. Most water resource assessments are faced with the problem of having a sample of information in either space or time and require methods to extrapolate that information to places or times where no observed information exists. Hence hydrological models of various types (deterministic rainfall-runoff models, stochastic rainfall or streamflow models, reservoir and system yield models, etc.) provide the main data generation tools and selecting the most appropriate models to use (out of a large number that are available worldwide) becomes one of the main decisions that has to be taken in the design of a water resources assessment study. Frequently the choice is restricted to those models that are available to the study team, or those that the study team are familiar with. It has been frequently suggested that the success of a modelling exercise depends less on the actual model being used and more on the experience of the model user. This is especially true where some level of manual calibration of the model parameters is used and where parameter transfer to ungauged situations is required (as it usually is in most practical water resource assessment studies).

Even relatively simple water resource assessments involve the use of several models or tools to achieve the desired result. For example a single catchment reservoir design could involve the use of a method to generate catchment average rainfall data from several point rainfall gauge data, the generation of a representative time series of monthly flow volumes with a rainfall-runoff model, the simulation of the reservoir behaviour under different abstraction and/or dam size scenarios and the determination of the yield, as well as the use of a design flood model to determine the required capacity of the spillway. Many of these different models have common data requirements and in the past it was frequently necessary to prepare the input data in different ways for different models, even when the output of one formed the input for another. SPATSIM is designed to bypass such inconveniences and provide an integrated data management system within the platform that is used to access a wide range of models.

The following sub-sections provide some examples of the way in which SPATSIM can and has been used in various types of water resource assessment.

3.1 RESERVE DETERMINATIONS LINKED TO WATER RESOURCE YIELD ANALYSIS

Several other sections in this report are dedicated to the use of SPATSIM for undertaking Reserve determinations using either the BBM approach or the Flow-Stressor Response method. However, the focus in this section is the link between the outputs from the various Reserve determination models and water resource assessment or yield determination models.

There are two main models within SPATSIM that are available to generate Reserve information; the Desktop Reserve model that generates Reserve requirement assurance tables and monthly time series of requirements and the Daily IFR model that generates daily Reserve requirements. The time series outputs from these models can be used with the two main rainfall-runoff models supplied with SPATSIM; the monthly Pitman model and the daily VTI model. Both of these have built-in reservoir simulation modules such that a reservoir can be located at the outlet of any of the sub-catchments within the spatial distribution system. If a reservoir is specified at a sub-catchment outlet, one of the optional data inputs from SPATSIM is a Reserve requirement time series and a simple set of operating rules for Reserve releases.

In simple situations where all the reservoirs are operated independently, the Pitman or VTI models can be used to determine the yield by simply repeating the model runs with various abstraction, dam size or operating rule scenarios until a specified demand is met with the required assurance (assessed by graphically comparing the time series of required draft with achieved draft, or by examining the time series of reservoir level, both using the TSOFT utility program). In more complex situations, where it is necessary to provide more detailed operating rules and priorities for different abstractions it will be necessary to make use of a water resources systems model. The Rapid Simulation model has been recently included within SPATSIM (although it is still under going further testing and refinement) to provide a simplified version of a systems model, while the DWAF, WRYM (Water Resources Yield Model) remains the standard approach within South Africa for this type of approach.

If the Desktop model has been used to generate the Reserve, a text file version of the Reserve assurance rule table can be generated and this is compatible with the input requirements of WRYM. If the Daily IFR model has been used the procedure would be to save the resulting time series of daily Reserve requirements to a text file (using the options to save as mean monthly flow time series), re-import those data into SPATSIM using an appropriate attribute, generate duration curve data to an array attribute and save those data to a text file. The final step would be to manually edit the duration curve table text file to remove those % point columns that are not required for input to WRYM.

The output time series data from WRYM are normally simple text files of simulated monthly flows at various nodes in the system under various scenarios. These can be imported into SPATSIM for further analysis. For example, one WRYM scenario may be to prioritise some of the abstractions (rather than the specified Reserve) and assess the resulting flow at a certain node in terms of the future ecological condition of the river. The time series of flow could be imported into SPATSIM and compared within the Flow-Stressor Response model with calibrated stress characteristics for a range of ecological categories.

In very simple situations the Reserve Licensing Model can be used to assess the effect of the Reserve on users, or the effect of new water uses on the Reserve where the artificial impacts on flow are limited to afforestation, abstractions from small distributed dams and direct abstractions from the river. The model relies upon having a natural flow monthly time series (available from the WR90 database or can be generated using the Pitman model), a table of Reserve assurance rules (from the Desktop Reserve model) and some information on the present day and future water use. Either of the last two requirements can be satisfied by generating new time series using the artificial influence parameters of the Pitman model. Alternatively, the Reserve Licensing Model allows parameters to be quantified and used to modify the natural time series. The evaluations against the Reserve requirements are based on graphical comparisons of flow duration curves.

In general terms, SPATSIM provides most of the facilities required to undertake Reserve assessments and to evaluate the effect of the Reserve on either present day or future water resource utilisation. Where additional models are required (such as the WRYM) relatively simple and efficient links have already been provided. In recent years, SPATSIM has been successfully used for Reserve determinations on, *inter alia*, the Olifants (16 sites), Thukela (16 sites), Buffalo and Kubusi (6 sites) and Kei (4 sites) rivers. It is likely to be used for several more in the near future. In some of these cases the system has been used to generate the natural flow data, while in others the basic data has been provided from the team undertaking the systems modelling component of the study.

3.2 BASIN SCALE DISTRIBUTED WATER RESOURCE AVAILABILITY

Within South Africa there are default time series of monthly flow data available from the WR90 database, while in many other parts of Southern Africa no such information exists and the only information available for assessing water resources are a limited number of raingauge records and observed flows at streamflow gauging sites. This means that the starting point for water resource assessments would normally be the generation of simulated flows at a range of points within the basin using a rainfall-runoff modelling approach after calibration against the available observed data.

SPATSIM provides the following utilities to facilitate this type of study:

- A range of data import utilities to ensure that observed rainfall, flow and evaporation data can be imported from a range of different original formats.
- Facilities for entering and editing model parameter values, as well as for viewing their spatial distribution.
- Facilities for generating parameter values from know relationships with physiographic (soils, geology, veregation, etc.) variables, through the 'intersection' of a sub-catchment boundary feature with a feature having the physiographic data as an attribute.
- Facilities for generating catchment average time series of rainfall or evaporation demand data from observed data at points, optionally using gridded data for additional weighting purposes.
- Facilities for setting up and applying one of the versions of the Pitman rainfall-runoff model (with all the associated options for including artificial catchment influences) and running the model using an automatic parameter optimisation routine.
- Facilities for viewing and analysing either the main model outputs stored within the SPATSIM database, or the internal model state variables that are stored within temporary binary files after each model run. The TSOFT utility provides a wide range of methods for comparing observed and simulated data to assist with a manual parameter calibration exercise.

The Pitman model with the revised ground water recharge and discharge routines is currently being applied to the Okavango catchment as part of a European Union funded international cooperation project. At the time of writing this report, the model had been calibrated for natural conditions and will now be used to assess various development and climate change scenarios (see Andersson et al., 2003 and other publications that will be generated during 2004).

The Pitman model has also been applied to the Kafue basin through the UNESCO FRIEND (Flow Regimes from International Experimental Network Data) project, by Mrs Mwelwa of Zambia, supported by DFID (UK). Mrs Mwelwa has been undertaking this study as part of an MSc project with the intention of developing a regional parameter set for the Pitman model. While large parts of the Kafue basin are relatively straightforward to simulate, the lower parts are influenced by quite complex interactions between the river and the floodplain areas of the Lukanga Swamps and the Kafue Flats, as well as the operation of the Itezhi-tezhi Dam (mainly for hydro-power generation). These influences presented calibration and model configuration challenges, which were nevertheless overcome within the SPATSIM system. The final calibrations are considered satisfactory given the quality of the input rainfall data, the available information on abstractions and the quality of the observed flow data. Other organizations within southern Africa have also applied the SPATSIM version of the Pitman model to catchments in Tanzania and Swaziland.

Where localised information is required at a daily scale, the VTI model (Hughes and Sami, 1995) is available within SPATSIM. This is a much more difficult model to calibrate as there are a larger number of parameters and the effect of changing their values on model results is less straightforward than with a monthly model. However, given some training on the use of the model and methods of calibration the model can be applied fairly efficiently. It has been demonstrated to be applicable to quite a wide range of catchments and different water resource problems in southern Africa (Sami and Hughes, 1996; Hughes, 1997; Hughes and Smakhtin, 1998; Smakhtin et al., 1998). A simpler alternative is to make use of the daily Patching model (Hughes and Smakhtin, 1996), which offers a method of extrapolating time series from gauged daily data with limited availability to ungauged sites where the flow duration curve characteristics can be estimated through some form of regionalisation.

3.3 GENERAL COMMENTS

There seems to be little doubt that SPATSIM can provide a viable platform for undertaking quite a wide range of different types of basin scale water resource studies. It is ideally suited to developing basin management authorities that have limited resources and require efficient access to basic information on water availability and use, as well as some relatively simple modelling tools. The advantages are as follows:

- The software is low cost.
- Basic training for several users can be achieved in 2 to 3 days.
- The spatial data are usually generated using ARCVIEW, which most water resource management agencies in southern Africa have access to.
- Data imports are usually quick and efficient and if a new time series format is not already covered, the IWR are available to add new code.
- SPATSIM provides a comprehensive range of data viewing, editing and graphing facilities that includes many of the basic, commonly used approaches to analysing and summarising time series data (seasonal distributions, flow duration curves, etc.).
- Several modeling tools that have been widely used within southern Africa are integrated into the software package.

4. SPATSIM NATIONAL DATABASE OF ECOLOGICAL RESERVE AND IFR DETERMINATIONS
DA Hughes

4.1 INTRODUCTION

The purpose of the National Database is to create a central repository of Reserve or IFR determination results that can be accessed by DWAF as well as their service providers to ensure that information is not lost and that the maximum benefit is gained from previous experience for future determinations. This document summarises the information content of the database, as well as providing guidelines for entering new data and using existing data. Reference to both Reserve and IFR determinations is used as some of the data that are included pre-date the concept of the 'Reserve' and were referred to as IFRs at that time. It is accepted, however, that the term 'IFR' has been largely superceded by the Reserve and the use of the term EWR or ecological water requirements.

One of the primary purposes of establishing the database was to create a facility for generating Rapid level ecological Reserve estimates for new sites in regions where more detailed determinations have already been undertaken (i.e. extrapolating). The standard DWAF procedure for this extrapolation is based on the Desktop Reserve model (Hughes and Hannert, 2003) and therefore the type of information stored in the database is dominated by the data requirements of the model, regardless of the method that was originally used for the more detailed determinations. The Desktop Reserve model was established with default parameter values for all the quaternary catchments of the country, although it was always accepted that these default values could be improved upon given further region-specific information. The National Reserve database and the standard SPATSIM data management and processing facilities are designed to provide all the tools that are required to make the best use of existing information to generate the most reliable results from the Desktop Reserve model.

It has been assumed that the National Reserve database will be applied by users at different levels:

Level 1 The simplest level of use is assumed to be the input, retrieval and review of information entered into the database by other users. The skills required for this level consist of a working knowledge of the basic data input, retrieval, display and output options available in SPATSIM.

Level 2 The second level of use is assumed to be the generation of rapid level Desktop Reserve estimates based on either the default national parameters, or using refined regional or basin-specific parameters established by other users. The skills required for this level consist of a working knowledge of the main SPATSIM options, an understanding of how to establish and run an external model using SPATSIM and an understanding of how to apply the Desktop Reserve model.

Level 3 The third level of use is assumed to incorporate level 2, but also include the calibration of the Desktop Reserve parameters at a regional or basin level. Additional knowledge and skills are required for this level that include a more in-depth understanding of the model and the effects of modifying some of the parameter values, as well as the ability to establish and run an application of the Desktop Reserve Calibration process.

This manual is not designed to provide basic guidelines for the use of SPATSIM and new users are referred to the online help facilities provided with SPATSIM and are highly recommended to attend a short course of the structure and use of SPATSIM. It is therefore assumed that all users of this manual are reasonably familiar with the basic concepts of SPATSIM, as well as the range of facilities that the package offers.

4.2 THE BASE INFORMATION CONTENT

The basic information that is contained within the National Reserve database consists of four spatial coverages (features) and a range of numeric or text attributes associated with each one. Any user may add additional features and attributes, but it should be recognised that their personalised version will then no longer be consistent with the standard version. While this will not necessarily cause problems, it will mean that greater care will have to be taken when exchanging information with other users.

4.2.1 The standard features

Four standard features (or spatial coverages) have been included in the database.

The ***quaternary catchment*** (Quat) feature is a polygon coverage that includes all the 1946 quaternary catchment boundaries within South Africa, Lesotho and Swaziland. These cannot be added to or modified within SPATSIM as there are no facilities included for manipulating polygons. If changes or additional (sub-quaternary) boundaries are required the shape file associated with this feature will have to be edited using a GIS package (such as ArcInfo or ArcView).

The ***WR90 river channel*** (River) feature is a line coverage that has been taken directly from the WR90 CDs available from the Water Research Commission. As with polygon coverages, there are no SPATSIM facilities to modify or add to line coverages and changes will have to be made through a GIS package. It should be noted that the names of the rivers within the original shape file itself are not complete and labeling the River feature is not very useful.

The ***Flow Gauges*** feature is a point coverage of some of the DWAF river flow gauging stations. At present this coverage is not complete and only has those stations included that have been used recently by the IWR. It is, however, possible to extend the coverage by using the adding points facility of SPATSIM. It is anticipated that this feature will be gradually extended to include all the flow gauging stations, which have useful records.

The ***IFR Sites*** feature is a point coverage of IFR or Reserve determination site locations and is the main coverage that will change within the database over time.

4.2.2 The Standard attributes

The information content of the database are stored as Attributes in SPATSIM and there are a range of different attribute types, including single numbers, text, 1- or 2-dimensional tables, time series and graphics. Attributes information is accessed through the points, line segments or polygons of the features (spatial elements). It therefore follows that combinations of spatial elements and attribute names provide a unique reference to specific information and that two features can have common attribute names. An explanation of the attributes that are included as part of the standard version of the National Reserve database are provided below.

4.2.3 Attributes associated with the Quat feature

Area (Cumulative and Incremental)*:* These are two single real number attributes that contain the cumulative (i.e. the total catchment area at the quaternary outlet) and incremental catchment areas (km^2). The standard database has values for all the quaternary catchments.

Desktop ERC parameters: This is a 2-D array (or table) attribute that contains the default values for some of the parameters of the Desktop Reserve model. The table consists of 7 rows (A to D Ecological Reserve Categories) and 8 columns (4 parameters for the annual maintenance low flow estimation equation, 4 parameters for the annual high flow estimation equation).

Desktop Hydro-Region & Desktop Local Hydro-Region: These are single integer attributes that contain the hydro-region numbers for the quaternary catchment. The former is based on a weighted 'average' of all the upstream quaternary catchment region numbers (where the weights are based on mean annual runoff), while the latter applies to the individual quaternary catchment and its internal triburaries.

Desktop Monthly Distributions: This is a 2-D array attribute that contains the default values for the monthly distribution parameters of the Desktop Reserve model. The table consists of 12 rows (months of the year) and 7 columns (1:Not used; 2:High flow distribution factors; 3:Low flow assurance rule shape factors; 4:Assurance rule upper shift; 5:Assurance rule lower shift; 6:Assurance rule low flow maximum; 7:High flow assurance rule shape factors);

Desktop Single Parameters: This is a 1-D array attribute that contains the default values for additional parameters of the Desktop Reserve model. The first row is the default region number applicable to the outlet of the catchment (i.e. including upstream flow influences). The second to seventh rows are the values of any of the adjustment factors made during the use of the model for this catchment (these can be saved during the model run). The next three are not currently used (they were part of the model version 1), while the final two are the default baseflow separation parameters.

Desktop Yield Parameters: This is a 1-D array attribute that contains the parameters of the yield reduction estimation equation used in the Desktop Reserve model (should that option be chosen). The model contains the facility to calculate the yield (for a specific reservoir size and return period) based on the natural flow regime of the river and then estimates the yield reduction if the Reserve is allowed for. The first three rows provide the parameters of a non-linear equation to estimate the yield for a 1:50 year drought, while the last three are the conversion factors for 1:10, 20 and 100 year droughts (the equations are based on the storage-yield curves in WR90).

Downstream area: This is a short text attribute that contains the Description Field information (quaternary name, e.g. D42A) of the next quaternary catchment.

IFR Extended Table (A, A/B, B, B/C, C, C/D, D): These are the seven 2-D array attributes that can be used to store IFR results based on the BBM but with extended flood information. There are 12 rows representing the months of the year. The first two columns contain the maintenance and drought low flow values ($m^3\ s^{-1}$). The next 14 columns contain the peak ($m^3\ s^{-1}$) and duration (days) values for 7 flood classes.

IFR Table (A, A/B, B, B/C, C, C/D, D): These are the seven 2-D array attributes that can be used to store IFR results based on the BBM with only two flood classes, but including drought flood peaks and durations.

MAR: This is a single real number representing the Incremental mean annual runoff in mm for the quaternary catchment.

Mean Annual Losses: This is a single real number representing the losses (in M m^3) that are estimated on the basis of the upstream catchment area, the net evaporation and the size of the quaternary catchment. These losses are applied when summing incremental runoffs to generate cumulative runoffs at the catchment outlet.

Monthly flows updated, WR90 cumulative and WR90 incremental: These are time series attributes that are used to store monthly flow volumes (in M m^3). The first attribute will not have data available for every quaternary catchment and can be used to store new data when they become available (i.e. from a specific basin study). The latter two attributes have data already entered for all quaternaries, the cumulative data being the sum of all the upstream incremental flows with the loss function (see the Mean Annual Losses attribute) applied.

Monthly IFR T/S (A, A/B, B, B/C, C, C/D, D): These are the seven time series attributes that can be used to store the results from the Desktop Reserve model.

Reserve Assurance Rules (A, A/B, B, B/C, C, C/D, D): These are the 7 2-D array attributes that are used to store the assurance rule results from the Desktop Reserve model. There are 17 rows representing a set of fixed percentage points on the assurance rule curves (the same as flow duration curves) and 12 columns representing the months of the year.

WR90 Zone Rainfall: This is a time series attribute that is used to store the WR90 time series of regionalised monthly rainfall depths (mm). The Geog ID element of the metadata associated with the time series gives the WR90 rainfall zone number that was used to generate the data.

4.2.4 Attributes associated with the Flow Gauges feature

Obs. Max. Daily Flow & Obs. Mean Daily Flow: These are the two time series attributes that are used to store the DWAF daily flow data. Two attributes have been included so that both the mean daily flows, as well as the peak daily flows can be extracted from the DWAF data files (see the time series import options in SPATSIM).

4.2.5 Attributes associated with the IFR Sites feature

Many of the attributes associated with the IFR sites feature are identical to those used with the quaternary catchment feature because it has been assumed that the Desktop Reserve model will be run with data from both features. However, there may be differences due to the site-specific nature of the IFR sites data. The descriptions of the attributes are not repeated if they have the same name as the quaternary catchment attributes.

Catchment Area (km^2): This is the single real number attribute that contains the area of the catchment upstream of the IFR site. It is mainly for information and is not required by the models.

Daily flows (Natural, Observed and Present Day): These are the three time series attributes that can be used to store daily flows (in $m^3\ s^{-1}$) under natural, observed and present day conditions. The 'Observed' flows would normally be historically recorded data including any trends due to changing land use or abstraction patterns. While the Desktop Reserve model does not use daily flow data, it is always useful to have the more detailed flow data for reference purposes if they are available. It is assumed that if daily flows are available and used during a Reserve determination they will be stored in the most appropriate of these attributes.

Desktop ERC parameters, Desktop Monthly Distributions, Desktop Single Parameters & Desktop Yield Parameters: These are the same attribute types as those associated with the quaternary catchment coverage.

Desktop Summary Table: This is a 1-D array attribute that stores summary information about the type of Reserve determination undertaken at a site. The first row is used for the year of determination, the second for the determination type (0=Desktop; 1, 2, 3=Rapid I, II, II; 4=Intermediate, 5=Comprehensive) and the third row for the confidence rating (0=very low to 5=high). The fourth row is for the Desktop Reserve model region number, the fifth for the monthly hydrological data type (0=WR90 only, 1=Updated information) and the sixth for the daily hydrological data type (0=None, 1=Observed data, 2=Naturalised data). The remaining rows are used to store the annual values of the various BBM components for different ecological categories but are not automatically updated at present. This attribute is mainly used in the 'Desktop Model Parameter Calibration', which is the SPATSIM external application that summarises all available Reserve determinations and can be used to establish localised parameters of the Desktop model for a specific region or basin (see later).

IFR Extended Table (A, A/B, B, B/C, C, C/D, D): These are the same attribute types as those associated with the quaternary catchment coverage.

IFR Pictures: This is a graphic attribute that can be used to store a photograph of the IFR site (using bmp or jpg files usually).

IFR Site Name: This is a short text attribute that is used to store the name of the IFR site and is required for the 'Desktop Model Parameter Calibration' external application.

IFR Table (A, A/B, B, B/C, C, C/D, D): These are the same attribute types as those associated with the quaternary catchment coverage.
MAR at the IFR Site: This is a single real number attribute that is used for storing the mean annual runoff (in M m^3) at the IFR site. The assumption is made that this is the MAR of the reference condition flows (usually, but not always, natural conditions).

Monthly Cum. Flows (Linked): This is a linked attribute that can be used to connect to a cumulative monthly flow time series attribute associated with the quaternary catchment feature. The link can be made to the WR90 flows or the updated flows. For further information on linking attributes see the SPATSIM help.

Monthly Flows (P.Day) & Monthly Flows (Updated): These are time series attributes used to store monthly flow volumes for present day and updated reference conditions (if different to WR90 data).

Monthly IFR T/S (A, A/B, B, B/C, C, C/D, D): These are the same attribute types as those associated with the quaternary catchment coverage.

Notes: This is a memo (extended text) type attribute that can be used to store any additional information about the IFR site or Reserve determination.

Reserve Assurance Rules (A, A/B, B, B/C, C, C/D, D): These are the same attribute types as those associated with the quaternary catchment coverage.

Stress-Flow Matrix: This is 2-D array attribute used to store the flows (in m^3 s^{-1}) associated with stress levels 0 to 10 for up to 5 ecological components, as well the integrated flow value.

4.2.6 Supporting data

As well as the information stored within the SPATSIM attribute database tables, additional supporting text files are included in the standard version of the National Reserve database. These are provided to facilitate loading default information to newly created points in (mainly) the IFR site feature. All of the text files are stored within the Spatsim/National/data sub-directory.

The first group of text files are for loading the default information for the Desktop ERC Parameters, Desktop Monthly Distributions and Desktop Single Parameter attributes. The procedure is to display the array information using the Add/Edit Array button and then to import the relevant text file using the 'Import from Text File' option (with the Table File type option selected). If it is required that any of the values in these files should be changed for a specific IFR site, do not edit the text files as this will then change the default values. Import the data into SPATSIM for that specific point and then modify the data in SPATSIM.

For the ERC Parameters there is a single file (***class.txt***) as these parameters do not change with region number.

For the Monthly Distributions there are 23 files (***mdist_1.txt to mdist_23.txt***), where the number refers to the Desktop Reserve model region (display the Desktop Hydro-region attribute for the nearest quaternary catchment to find the most appropriate region number to use for a new IFR point).

For the Single Parameters there are 23 files (***single_1.txt to single_23.txt***).

The second group of files contain the complete information for the Desktop ERC Parameters, Desktop Monthly Distributions and Desktop Single Parameter attributes for all the quaternary catchments in the country (***class_v2.txt, monthly_v2.txt and single_v2.txt***). These were originally used to populate the database for the quaternary catchment feature and should not be normally required. However, if for some reason it is necessary to restore all the default values for these three attributes (associated with the Qaut. feature) then the data can be imported using the '*Attribute -> Import or Edit ->Text Table to Array*' menu option and selecting the appropriate text file.

The third group of files contain all the quaternary catchment information for the downstream area attribute (***downquat.txt***), the Desktop hydro-region number (***newreg.txt***) and the Desktop yield parameters (***yieldpar.txt***). As with the second group it should not be necessary to use these as the data have already been imported into SPATSIM.

4.3 PROCEDURES FOR ADDING NEW INFORMATION ON A RESERVE DETERMINATION

This section is designed to provide guidelines on the procedures for adding new information about a Reserve determination and also specifies the most appropriate format for the original data. It is assumed for some of the requirements that the original data will be generated using the Desktop Reserve model (either the stand alone version or the SPATSIM version). However, that is not a strict requirement, it simply makes generating the required information simpler.

4.3.1 Required information

This list of required information should be passed on to any of the DWAF service providers that are undertaking Reserve determinations so that they can ensure that the required information is generated during the determination and returned to DWAF at the conclusion of the study.

Location of the IFR site in decimal degrees. This information is required so that a new point in the IFR sites feature can be created at the correct location. Adding new data points is simple (see the Help on Points – Add, Move & Delete) and the only information required is the location in decimal degrees to three decimal places. Check that the point lies on one of the lines of the river channel feature (unless it lies on a tributary not included in the feature).

Hydrological data used in the determination. This may include reference, present day and historical (observed) data and may be monthly and daily. The data need to be saved in a format that can be accessed by SPATSIM and the most common format is the simple text 'spreadsheet' type (i.e. text files with 1 line representing 12 months of data preceded by the year for monthly data and 1 line representing 1 months data preceded by the year and month for daily data. All the data values should be separated by at least one space). The type of data needs to be specified as part of the header information in the file so that the SPATSIM user knows which time series attribute to use to store the data. Monthly data can be supplied as either volumes (usually in M m^3) or mean monthly flow (in m^3 s^{-1}).

MAR at the IFR Site. The reference mean annual runoff (in M m^3) at the IFR site is important, especially if the flow data used in the determination is not for the exact same point on the river.

Catchment area above the IFR site in km^2. This has been included for reference purposes and is not actually used in any of the models.

Details of the determination type. This is the information that corresponds to the Desktop Summary Table attribute and includes the year of determination, the type of determination, the confidence rating, the Desktop model hydro-region number and the types of hydrological data that were available.

Desktop single parameter table. This information includes the Desktop model hydro-region number and the size of the various manual adjustments made during the use of the Desktop model. It also includes the baseflow separation parameters (Alpha and Beta). This information will only be available if the SPATSIM version of the Desktop model was used during the determination and is not essential. If the stand-alone version of the Desktop model was used and the default values were adjusted, it is important that notes on the adjustments made are recorded so that the result can be recreated within SPATSIM.

Desktop ERC Parameters and Desktop Monthly Distributions. These are also only relevant if the Desktop model has been used in the determination and if any changes were made to the default values for the specific hydro-region.

IFR Tables. These are the BBM tables (for each ERC used within the determination) with either 2, or up to 7, flood classes.

Monthly IFR time series. These can be supplied if either the Desktop Reserve model or the Daily IFR model were used in the determination. They should be supplied in the same format as the hydrological data referred to above.

Reserve Assurance Rule Tables. The attributes associated with this information contain more percentage points than the normal text output from the Desktop Reserve model. The text output can therefore not be used to generate the required SPATSIM data. However, if monthly IFR time series data have been supplied then the assurance information can be generated by using the ‘Procedure -> Generate DC’s’ menu option in SPATSIM. This is because the assurance rules are the direct equivalent of duration curves.

Stress v flow relationships. This information will be available if the Flow Stressor Response approach had been used in the determination.

Notes: The notes attribute can be used to store any specific information that has not been captured by the numeric data. Any information can be entered including the contact details of the team that carried out the determination, any details of deviation from normal practice or default parameters in the use of models (such as the selection of a different category for the Desktop model assurance rules than the specified ecological Reserve category) and the source of the hydrological data (such as what models were used to generate the data).

The effort required to import all the information into SPATSIM largely depends upon the format of the data and the amount of pre-processing and editing that will be required. If the data are supplied in a format compatible with SPATSIM only minimal effort will be required. The data can be supplied in spreadsheets, in which case it will have to be copied to text files first.

It is expected that during 2003 some of the information requirements will be expanded. For example a standard hydraulic model is expected to be included as part of SPATSIM and it will be useful to store the channel cross-section and hydraulic calibration data that was used. A further example is the possible future development of a stressor response approach for high flows incorporating information about geomorphological processes. It may also be possible to design a facility that allows some of the details of a DRIFT type Reserve determination to be captured, as well as information about a water quality Reserve determination.

4.4 THE DESKTOP RESERVE MODEL AND SITE SPECIFIC RESERVE DETERMINATIONS

The Desktop Reserve model has been structured to be highly flexible in the way in which it can be applied. In its simplest form, all the regional default parameter values that have been established for the whole of South Africa are accepted (i.e. not modified). However, experience suggests that there are frequently site, or region, specific issues that have not been adequately catered for in the original parameter values such that modifications can be made that will generate a more reliable and confident result. There are essentially two approaches to generating site specific results, both of which rely upon somewhat higher levels of expertise in the use of SPATSIM and the Desktop model.

- Manual adjustment of the Desktop model parameters and results for individual sites (addressed in this section).
- Recalibration of the Desktop model parameters for a group of sites in a region or river basin based on more detailed Reserve determinations at example sites (addressed in the following section).

4.4.1 Running the Desktop Reserve model from SPATSIM

Setting up an application of the model

The assumption has been made that all of the attributes referred to in Section 4.2 exist in the individual users version of the National database and that a point exists in the IFR Sites Feature that represents the site where a determination is required. The user then selects the

‘Application -> Run Process -> Select Items’ menu item, clicks on the ’Select Spatial Element’ icon and then on the point representing the site. Continue by clicking the ‘Start Process’ button and select (using a double click) ‘Desktop Reserve Model’ from the list of external processes available. The requirements for the Desktop model will then be displayed.

Ensure that the IFR Sites Feature is highlighted and then select the appropriate Attributes to satisfy the model requirements (highlight the required Attribute in the list and then double click the appropriate blank space in the model requirement list). The following notes provide guidelines on the selection of the correct attributes (see Section 4.2.5):

- Requirement 1 is already set and should not be changed.
- Requirements 2 and 3 can be ignored.
- Requirement 4 is not essential but can be used by selecting the catchment Area (km^2) attribute.
- Requirement 5 refers to the Desktop Single Parameter attribute.
- Requirement 6 refers to the Desktop Monthly Distribution attribute.
- Requirement 7 refers to the Desktop ERC Parameter attribute.
- Requirement 8 refers to the Desktop Yield Parameter attribute and is optional.
- Requirement 9 refers to either an IFR Table or an IFR Extended Table attribute. The user should select the attribute that conforms to the ecological category to be used for the determination.
- Requirement 10 refers to the assurance rules that can be saved back to SPATSIM after the model has been run and a Reserve Ass. Rule attribute can be selected which has the appropriate ecological category label.
- Requirement 11 refers to saving just the assurance rules for low flows (i.e. excluding all high flow requirements). There is no standard attribute available for this requirement, as it is normally not used (an internal text file saving facility allows these data to be saved). If it is important, the user will have to create a new Array Type attribute with a format file of ‘Monthly Duration Curve Tables of % Points’.
- Requirement 12 refers to the monthly flow time series that are to be used to drive the Reserve determination. The attribute normally used would be the monthly cumulative flows, either linked to the quaternary catchment feature or using the Monthly Flows (updated) attribute of the IFR sites coverage. It will be necessary to make the link (see SPATSIM Help) or import suitable flow data into SPATSIM.
- Requirement 13 refers to the final result as a time series of monthly Reserve requirements. An appropriate Monthly IFR T/S attribute should be selected on the basis of the ecological category to be used.

All of the attributes that are labeled as ‘Req’ (rather than ‘Opt’) must have data entered before the model can be run and Section 4.2.6 provides information on where the default data values can be located. The attributes that are optional (‘Opt’) refer to parts of the model that are not essential, or to data that can be saved after the model has been run. Clearly, if the user wishes to save these data, an attribute must be specified when the model is established.

If a mistake is made in setting a requirement it can either be over-written by simply double clicking when the correct attribute is highlighted, or the ‘Clear Req’ment’ button can be used. The ‘Save Requirements’ button is used when all the requirements have been specified. The user then saves the setup by clicking the ‘To a New Record’ button and providing the setup with a suitable description. If an old setup is to be replaced use the ‘To Selected Record’ button after selecting an old setup from the table displayed. The Process Requirement Table is a list of all external applications that have been set up for a specific users database installation. If some are no longer required then the minus sign icon can be used to delete the highlighted setup.

The ‘Run Process’ button can then be used to run the Desktop Model for the first time. Subsequently, the ‘Application -> Run Process -> Directly’ menu option can be used to re-run the same application of the Desktop model without having to specify the model requirements again. Click the menu item, select the Desktop Reserve Model from the list of processes, then search for the ‘Description’ of the required setup, click ‘Read Data’ and then ‘Run Model’.

Running the model

The first screen summarises the monthly flow data that the user has specified to be used to drive the Reserve determination. The only possible user intervention at this point is to adjust the MAR of the data (effectively a linear scaling up or down) to make the time series more representative of the IFR site. This is especially relevant when using the default WR90 data associated with the quaternary catchment coverage and if the IFR site is not exactly at a quaternary catchment boundary. There are no clear guidelines that can be offered about how to calculate the required adjustment and it is usually necessary to use individual judgement based on an assessment of the incremental flow contribution of the sub-catchment in which the IFR site is located and the position of the site within that sub-catchment.

The nest screen provides the annual and monthly estimates of the main BBM components (maintenance low and high flows and drought low flows) for the selected ERC. The first step is to ensure that the correct ***Final ERC*** is specified, after which the user has several options in terms of intervention and the ability to modify the results.

The ***Parameter Source*** option allows the user to base the determination on the Desktop model parameter values that were loaded for the specific site (i.e. the values contained within the Desktop Single Parameter, Desktop Monthly Distribution and Desktop ERC Parameter attributes for the current site), default National data (contained within the RESDSS_V2.PAR textfile – which should never be edited), or to ignore the model calculations and use pre-quantifed Defined IFR Table values. The latter would be stored within the IFR Table or IFR Extended Table attribute that was specified during the model set up and entered using the normal array attribute editing facilities of SPATSIM. The only option that allows the Monthly Distribution Type to be changed is the Default National Data option, otherwise the region would have to be changed by editing the value in the Desktop Single Parameter attribute.

There are several ***Manual Adjustments*** that can be made, but note that the Parameter Source selection should not be changed once the adjustments have been started. There are three possible manual adjustments that can be made to the annual values. Increases or decreases to the drought low flows, maintenance low flows and maintenance high flows. Each click of the arrow buttons causes a 0.1% change in the annual values. Note that the maximum values of the drought low flows in each month are determined by the minimum flow volume in the time series of flows that are being used to drive the determination. Changes to the annual drought low flow total may therefore not be possible. The other manual adjustments that can be made are to the seasonal distributions of the drought and maintenance low flows. A higher value of the parameters gives rise to a more peaked seasonal distribution (i.e. higher wet season and lower dry season flow requirements). The default values are dependent upon the ERC.

The reasons for modifying the default values will usually be based upon specialist expert opinion for the specific site in question, or upon the principle of matching the results to a nearby site which has been the subject of a more detailed determination.

At this point in the model it is possible to view the seasonal distributions graphically, as well as output the BBM table and a summary of the flow data to a text file or printer. The '***Set IFR Rules***' menu option moves to the next part of the model, which displays the assurance rule curves for the selected month of the year. There are five parameters which determine the shapes of these curves for each month of the year and they can all be edited at this point. While it is possible to edit the parameter values and then continue with the model, it is recommended that the most suitable values are determined using the editing facilities for two or more key months and then exit the Desktop model and manually edit the relevant parameters in the Desktop Monthly Distribute attribute for the IFR site. The model can then be re-started and the changes will be recognised. Note that if an ERC of lower than B (i.e. B/C, C, C/D or D) is used then the Low Flow Max. parameter is adjusted upwards automatically. Users therefore need to be careful when adjusting the parameter values within SPATSIM (i.e. enter a value which is appropriate to a B ERC, not the ERC being used for the site). At this point in the model the assurance rules can be output as tables (in $m^3 s^{-1}$ mean monthly flow, or as total monthly volumes in Mm^3) to a text file or the printer. If at any point on the curves the estimated requirements exceed the reference flows the Reserve flows will be automatically reduced in the output unless the rule output control option is set to 'Design flows unlimited' (see the Write Rules or Print Rule -> Control menu option).

The final part of the model generates the full ***time series of requirements*** based on the reference flows and the assurance rules. This part of the model is mainly to generate display and output information and there are no user intervention options. It is possible to save the generated Reserve requirement time series to a text file, to add a text file version of a time series for comparison purposes (adding a time series of present day flows for example) and to output the graph to a printer or graphics file. There is also an option to determine the effect of allowing for the Reserve on the reduction in yield for different reservoir sizes and return periods. For this option to function it is necessary to include a reference to an attribute containing the parameters of the yield estimation equations (requirement no. 8) in the original setup of the model.

Saving the results

Clicking return for all the different screens that are part of the model will bring the user back to the first screen of the process and the 'Save Results' button will be activated. There are five options for saving data (depending upon which of the model requirements have had attributes associated with them at setup time):

- ***Desktop Single Parameters***: Selecting this option allows all the manual adjustments (% MAR, annual value and seasonal distribution factors) and changes made to the monthly distribution type to be saved to SPATSIM.
- ***IFR Table Data***: This option allows the BBM table to be saved and the user is required to specify the duration of the required flood events. Even if an extended table type (7 flood classes) has been selected, at this point only two types of flood are considered (M. Flood and M. Fresh). If the total flood volume needs to be further distributed then this will have to be done manually using the attribute editing facilities of SPATSIM.
- ***Total Flow Assurance Data***: These are the tables of assurance data (the same as flow duration curves) for total flow (i.e. low and high flows combined).
- ***Low Flow Assurance Data***: These are the same as the previous item, except that the high flow component of the Reserve is excluded.

- ***Total IFR Time Series***: These are the time series of monthly Reserve requirements as generated by the model.

To be able to save any of the above data, it is necessary to run to at least that point in the model. For example, if the screen that shows the assurance curves is not accessed at least once, then these data are not generated and cannot be saved.

4.5 RE-CALIBRATING THE DESKTOP RESERVE MODEL FOR SPECIFIC REGIONS OR BASINS

A separate SPATSIM application (***Desktop Parameter Calibration Model***) has been established to assess some of the parameter values of the Desktop Reserve model and to determine more appropriate parameter values (for different regions of the country) where necessary. It is not necessary to establish this application, as it has already been set up and will find all points in the IFR Sites Feature that have data associated with the following attributes:

- IFR Site Name.
- An IFR table representing at least one ecological category contained in attributes IFR Table (A, A/B, B, B/C, C, C/D, D) or IFR Extended Table (A, A/B, B, B/C, C, C/D, D).
- Desktop Summary Table.
- Desktop ERC parameters (only required for a single point and these data are already part of the database and associated with the 'Desktop Control Point').
- Desktop Single Parameters (specifically the baseflow separation parameter values).
- Monthly Cum. Flows (Linked) or Monthly Flows (Updated). One or both of these should have data associated with them.
- MAR at the IFR Site.

The necessity for the model lies in the fact that the original Desktop Reserve model parameters were established with a limited number of results and it was therefore difficult to establish representative regional values. Additional information is being added to the database all the time and if the Desktop Reserve model is to be used to generate the 'best guess' Reserve information then it is inevitable that it will need to be locally calibrated from time to time.

To run the model, simply select the SPATSIM menu item ***Application -> Run Process -> Directly***, select ***Desktop Parameter Calibration Model*** from the list of processes and then select the ***Desktop recalibration model*** description from the application table. Before reading the data, the user should decide whether the analysis should be based on the Regional Flow data (from WR90 and stored in the Monthly Cum. Flows (Linked) attribute), or on Site Specific Flows (stored in the Monthly Flows (Updated) attribute). When this selection has been made, click on the ***Read Data*** button, then on the ***Run Model*** button and then the ***Selection*** tab to get the options to select specific sites for displaying (see Fig. 4.1). The user can now select those IFR sites that are to be included in the calibration exercise using the following range of criteria:

- Date of determination. The two spin buttons at the top of the screen allow determinations that were undertaken outside a range of years to be excluded.
- Reserve categories. The 'Classes' selection allow only some ERCs to be included.
- Specific determination types can be included and excluded (see the Desktop Summary Table attribute data).
- Determinations with certain confidence ratings can be included or excluded (see the Desktop Summary Table attribute data).
- The sites can also be selected on the basis of the type of hydrological data that were available (see the Desktop Summary Table attribute data).

- The ‘Data Type’ and ‘Total or High Flows’ selections allow the user to focus on maintenance and drought low flows and/or high flows or total flows. It is frequently convenient to look at these separately to avoid cluttering the calibration graphs. Do not change the High Flow/Total Flow Equation Type (Type 2 should be selected).
- The ‘Regions’ selection allows the user to choose only those sites that fall into specific Desktop model regions (see the Desktop Summary Table attribute data).
- For graphical display purposes the estimation lines (Class Lines) for some ERCs can be included/excluded.

The ***Print Summary*** button can be used to print a summary of the annual volumes (for maintenance low and high flows and drought low flows) for all the sites that are available. The ***Colours*** tab can be used to changes the colours that are used in the graphical display, as well as the maximum and increment values for the two axes. Once the site selection has been made return to the ***Graph*** tab (Fig. 4.2) and click on the ***Refresh Plot*** icon. The ***X Log/Lin*** button can be used to switch between a linear and logarithmic display of the x-axis, while the ***Statistics*** button can be used to display the mean sum of squares difference between the plotted points and the current estimation lines. The ***Save to Disk*** icon is used to save the graphical plot to either a windows metafile (wmf) or a bitmap file (bmp).

It is now possible to modify the parameter values of the different estimation lines to achieve a better fit to the selected points.

This section is designed to offer some guidelines on changing the default curve parameters to achieve improved fits to a group of selected sites.

There are several basic principles that should be followed each time a calibration is attempted:

- Do not only calibrate a line for a single category. It is much better to calibrate all the category lines, even if there are no points available for some categories (some extrapolation will then be required). There should be some logical sequence of parameter value changes between the different category lines, although they do not need to be evenly spaced (as they are by default).
- Start with the low flow estimation lines.
- Remember that the D category line and the drought low flow estimation lines are the same.
- Be careful not to calibrate using outliers.

4.5.1 Calibration guidelines

To modify the shapes of the curves, click on the appropriate category in the ***Class Selection*** box then highlight the current value of the parameter to be changed and edit the value. Then click on the ***Save*** button, followed by the ***Refresh Plot*** icon. It is largely up to the individual user to make choices about which parameters to modify to achieve the desired result. Fig. 4.3 and 4.4, as well as the text below provide some further details of the effects of changing the parameter values.

Fig. 4.3 illustrates the effects of changing the parameter values that determine the relationship between annual low flow requirements and the hydrological index. Parameter ***MP1*** mostly controls the curvature of the line and also has a substantial impact on the estimates at high index values. Parameter ***MP2*** largely controls the vertical positioning of the line, but changes have a small impact on the curvature of the lines. Parameter ***MP3*** also affects the curvature of the line, but does not change the line at very low index values. Parameter ***MP4*** simply causes a vertical shift in the line.

Figure 4.4 illustrates the effects of changing the parameter values that determine the relationships between the annual maintenance high flow requirements and the hydrological index. The B category default line has been included for reference purposes. Parameter ***TP1*** controls the curvature of the line at moderate to low index values (Fig. 4.4A), while ***TP2*** also affects the curvature, impacting progressively more as the index value increases from a value of 1 (Fig. 4.4B). Changes in parameter ***TT1*** causes a systematic vertical shift along the whole line (Fig. 4.4C), while ***TT2*** has a small effect, mainly at high hydrological index values (Figure 4.4D illustrates that it affects the slope of the line after an index value of 15).

Figure 4.1 Site selection screen for the Desktop Parameter Calibration model.

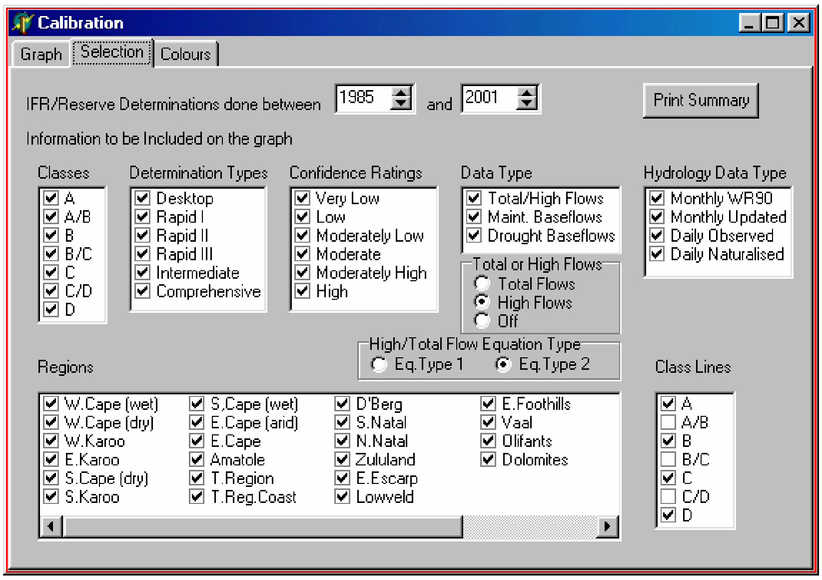
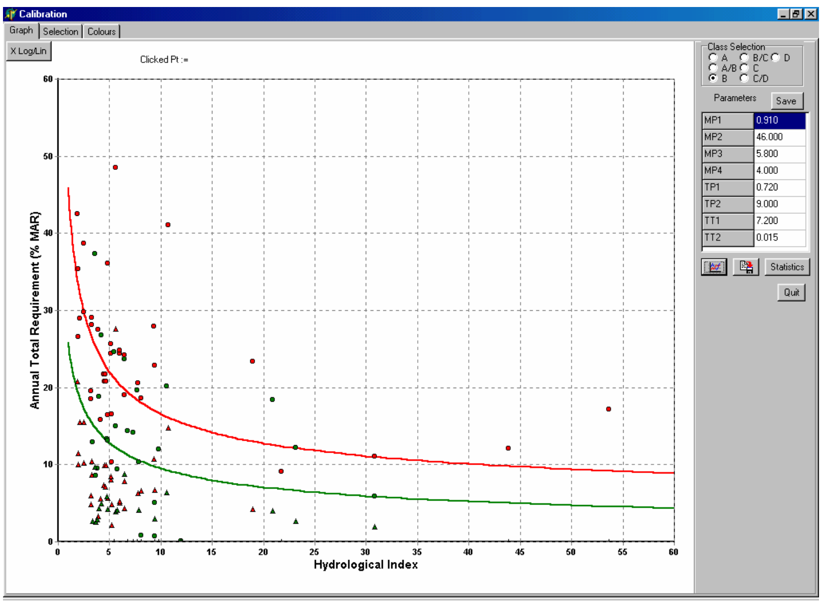


Figure 4.2 Example of a graphical plot.



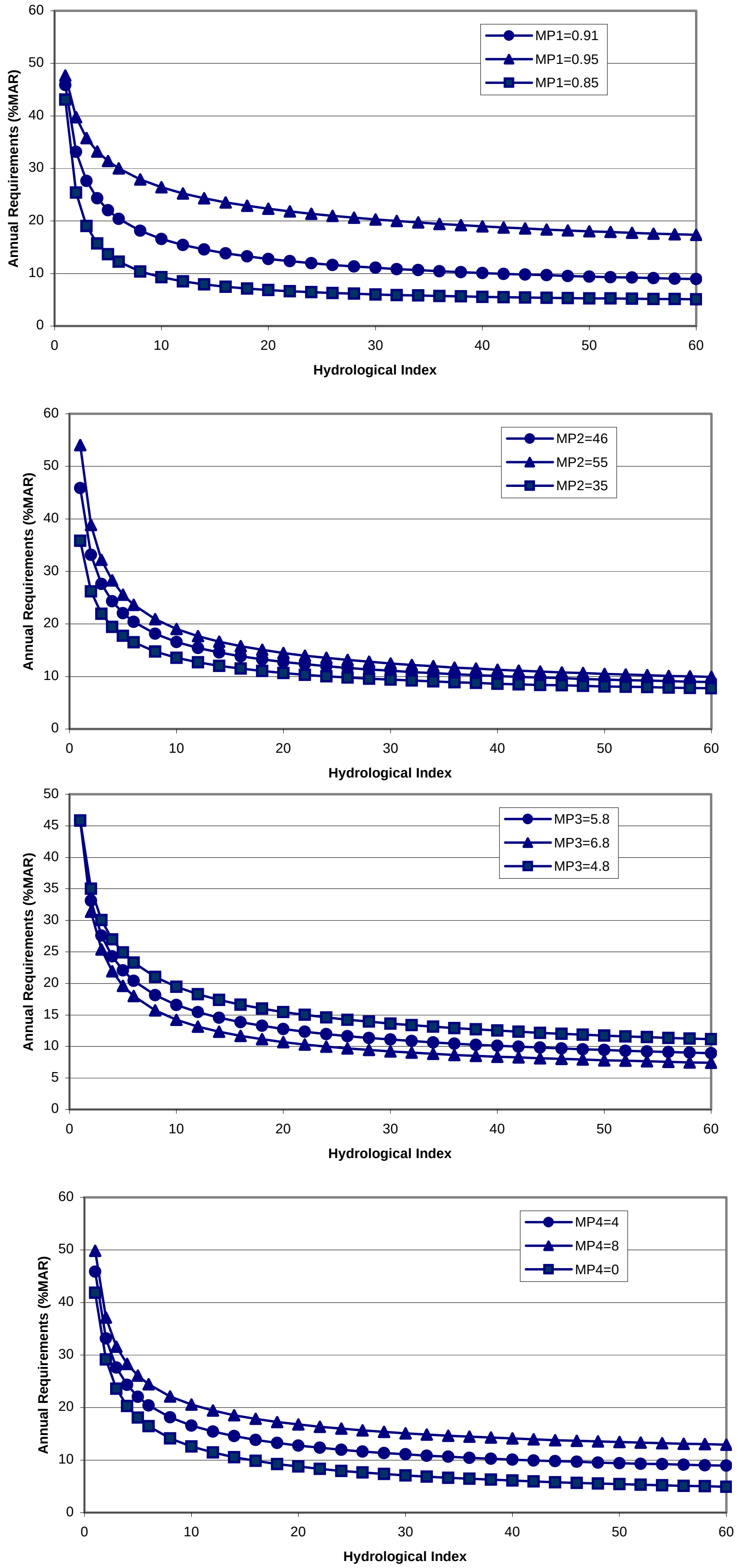


Figure 4.3 Effects of changing the four low flow estimation parameters (unless otherwise specified the parameter values are MP1=0.91, MP2=46, MP3=5.8, MP4=4)

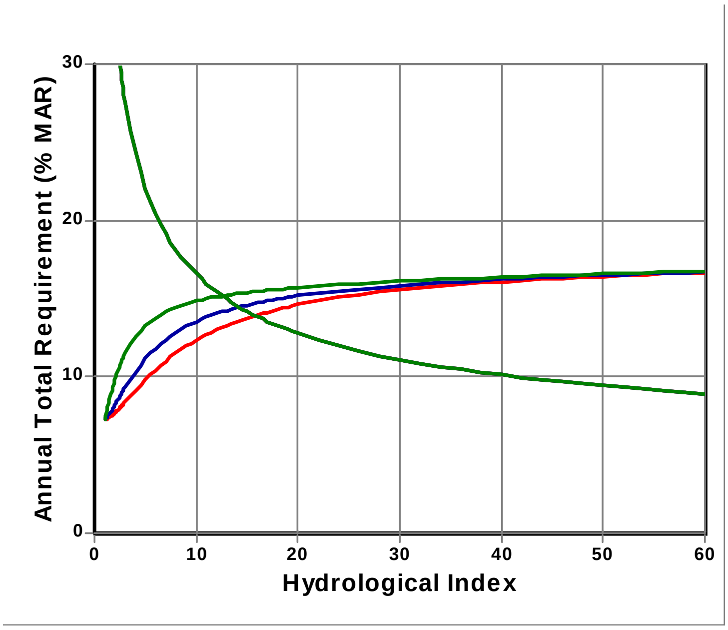


Figure 4.4A Effect of changing TP1 (Top=0.5, Middle=0.72, Bottom=0.9; other parameters, TP2=9, TT1=7.2, TT2=0.015)

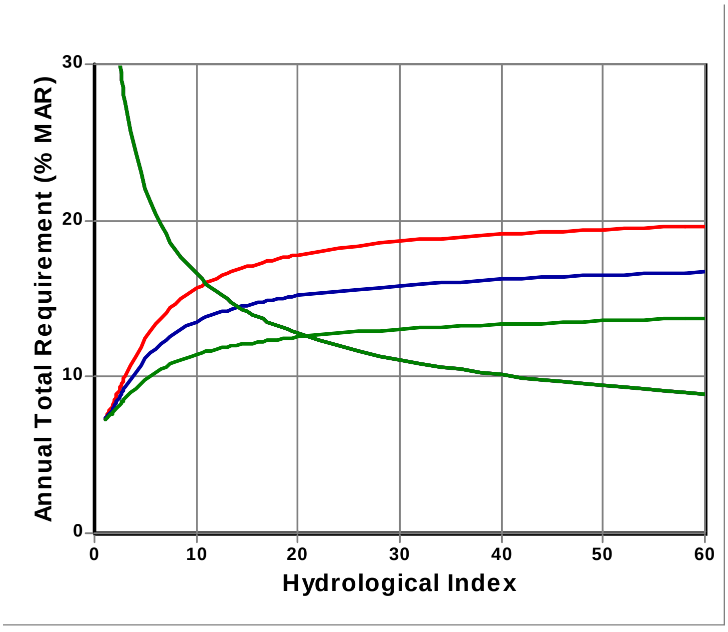


Figure 4.4B Effect of changing TP2 (Top=12, Middle=9, Bottom=6; other parameters, TP1=0.72, TT1=7.2, TT2=0.015)

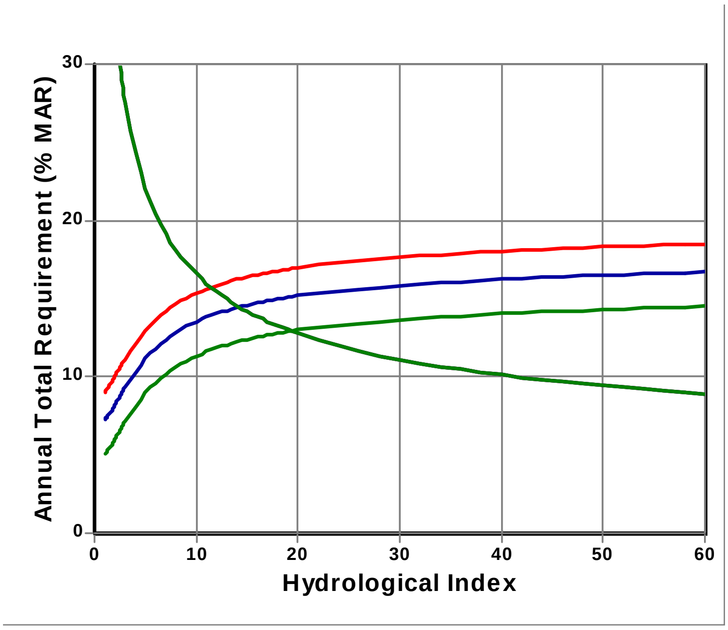


Figure 4.4C Effect of changing TT1 (Top=9, Middle=7.2, Bottom=5; other parameters, TP1=0.72, TP2=9, TT2=0.015)

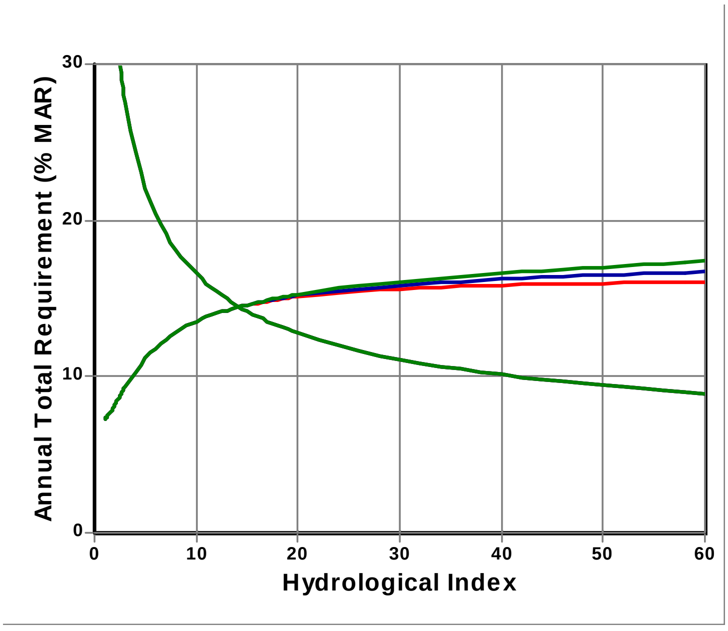


Figure 4.4D Effect of changing TT2 (Top=0.03, Middle=0.015, Bottom=0.0; other parameters, TP1=0.72, TP2=9, TT1=7.2)

4.5.2 Updating the database

Once the parameter values have been finalised for a group of sites, the user should return to SPATSIM and modify the appropriate attribute values. This should be done for both the quaternary catchment (***Quat***) feature as well as the ***IFR Sites*** feature. In both cases the appropriate attribute is the ***Desktop ERC Parameters*** array. While this can be achieved by simply editing the array attribute (using the ***Add/Edit Array*** icon) manually for every polygon and point in the two features that fall within the specific area or basin being calibrated, there is a quicker method. Manually edit the values for a single point or polygon and then save these data to a text file (using the ***Write to File*** button), selecting the option to invert the array, but not to write the row and column titles.

This text file can now be edited (use a suitable text editing program such as Notepad) in the following way to prepare an input text file for SPATSIM:

- Insert the name (i.e. the label that is displayed in SPATSIM) of one of the IFR points on the first line of the text file before the first data value. Ensure that there is at least one space between the name and the first data value.
- Copy the whole block of data (should be 8 lines) and paste it back at the end of the file so that you have one block for every point and polygon that you need to change in SPATSIM.
- Edit the names at the start of each block so that they are exactly the same as the names of the points or polygons in the area of concern.
- The final result should look something like Table 4.1

Select the IFR Sites feature and the Desktop ERC parameter attribute and then select '*Attribute -> Import or Edit -> Text Tables to Array*' from the main menu, locate and select the prepared import text file and the data will be imported. Repeat the process for the Quat feature and Desktop ERC parameter attribute and then carry out some checks to ensure that the data have been imported correctly.

4.5.3 An example – re-calibrating the model for the Olifants River, Mpumalanga Province

Figure 4.5 illustrates the default baseflow estimation lines together with all the Olifants data points (the C outlier is in the Olifants region but not in the Olifants basin and can be ignored) and suggests the following changes:

- The maintenance B category line should be lowered.
- The maintenance C category line should remain the same.
- The Maintenance D category and drought low flow line should be lowered.
- The Blyde River site has not been included, but is not considered to fall within the Olifants region (it is in the Eastern Escarpment region). Therefore the wetter and more reliably flowing tributaries in the east are excluded from this recalibration.

The consequence of these changes for the other lines can be extrapolated as follows:

- The maintenance A, A/B, B/C and CD category lines should be lowered.
- This means that, relative to the default lines, there is less distinction between categories A to C and more between C to D.
- This may be a 'large river' issue and there is no evidence to suggest that the same principles would apply to the smaller tributaries.

Table 4.1 Example of an import text file for Desktop parameter values

```
Mtata1      0.900      0.905      0.910      0.915      0.920      0.925      0.930
     79.000     61.000     46.000     37.000     28.000     24.000     20.000
      6.000      5.900      5.800      5.600      5.400      5.250      5.100
      8.000      6.000      4.000      2.000      0.000     -2.000     -4.000
      0.900      0.800      0.720      0.660      0.610      0.580      0.550
     13.000     11.000      9.000      7.750      6.700      5.900      5.500
     10.000      8.500      7.200      6.200      5.500      4.900      4.500
      0.015      0.015      0.015      0.015      0.015      0.015      0.015
Mtata2      0.900      0.905      0.910      0.915      0.920      0.925      0.930
     79.000     61.000     46.000     37.000     28.000     24.000     20.000
      6.000      5.900      5.800      5.600      5.400      5.250      5.100
      8.000      6.000      4.000      2.000      0.000     -2.000     -4.000
      0.900      0.800      0.720      0.660      0.610      0.580      0.550
     13.000     11.000      9.000      7.750      6.700      5.900      5.500
     10.000      8.500      7.200      6.200      5.500      4.900      4.500
      0.015      0.015      0.015      0.015      0.015      0.015      0.015
T20C      0.900      0.905      0.910      0.915      0.920      0.925      0.930
     79.000     61.000     46.000     37.000     28.000     24.000     20.000
      6.000      5.900      5.800      5.600      5.400      5.250      5.100
      8.000      6.000      4.000      2.000      0.000     -2.000     -4.000
      0.900      0.800      0.720      0.660      0.610      0.580      0.550
     13.000     11.000      9.000      7.750      6.700      5.900      5.500
     10.000      8.500      7.200      6.200      5.500      4.900      4.500
      0.015      0.015      0.015      0.015      0.015      0.015      0.015
T20D      0.900      0.905      0.910      0.915      0.920      0.925      0.930
     79.000     61.000     46.000     37.000     28.000     24.000     20.000
      6.000      5.900      5.800      5.600      5.400      5.250      5.100
      8.000      6.000      4.000      2.000      0.000     -2.000     -4.000
      0.900      0.800      0.720      0.660      0.610      0.580      0.550
     13.000     11.000      9.000      7.750      6.700      5.900      5.500
     10.000      8.500      7.200      6.200      5.500      4.900      4.500
      0.015      0.015      0.015      0.015      0.015      0.015      0.015
T20E      0.900      0.905      0.910      0.915      0.920      0.925      0.930
     79.000     61.000     46.000     37.000     28.000     24.000     20.000
      6.000      5.900      5.800      5.600      5.400      5.250      5.100
      8.000      6.000      4.000      2.000      0.000     -2.000     -4.000
      0.900      0.800      0.720      0.660      0.610      0.580      0.550
     13.000     11.000      9.000      7.750      6.700      5.900      5.500
     10.000      8.500      7.200      6.200      5.500      4.900      4.500
      0.015      0.015      0.015      0.015      0.015      0.015      0.015
```

The changes that were made to the Olifants parameters were all to MP2 (although changes to MP4 would also have worked):

A category	MP2 changed from 79 to 48
A/B category	MP2 changed from 61 to 38
B category	MP2 changed from 46 to 31
B/C category	MP2 changed from 37 to 29.5
C category	MP2 unchanged from 28
C/D category	MP2 changed from 24 to 23
D category	MP2 changed from 20 to 18

The new estimation lines are illustrated in Fig. 4.6. Without information about the requirements for A/B and A category rivers, the parameters for these lines must remain in doubt.

Attempts to identify parameter changes for the high flow estimation equations were not successful as there was too much scatter in the individual points. The default equations were therefore retained.

Figure 4.5 Default B, C and D (also drought) maintenance low flow estimation lines and Olifants River points.

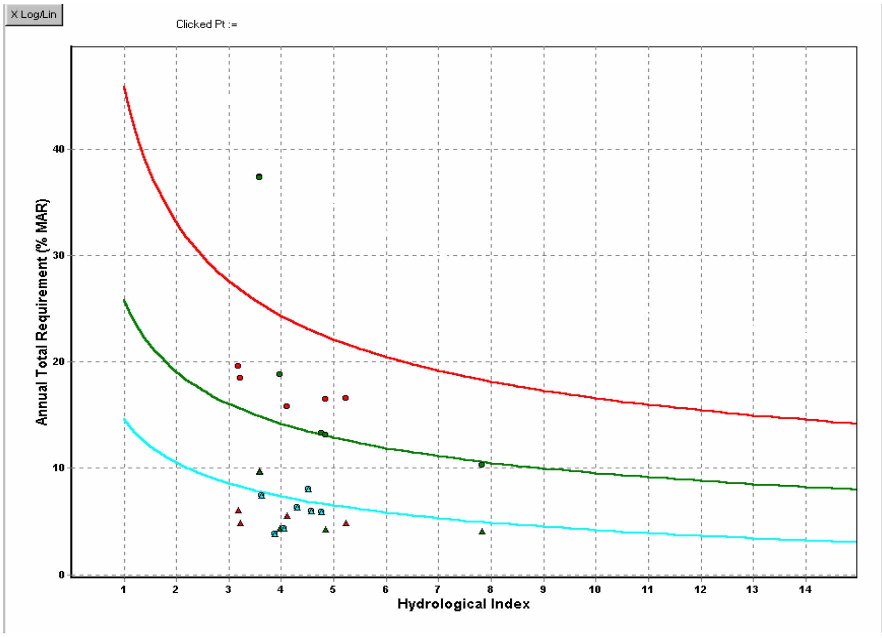
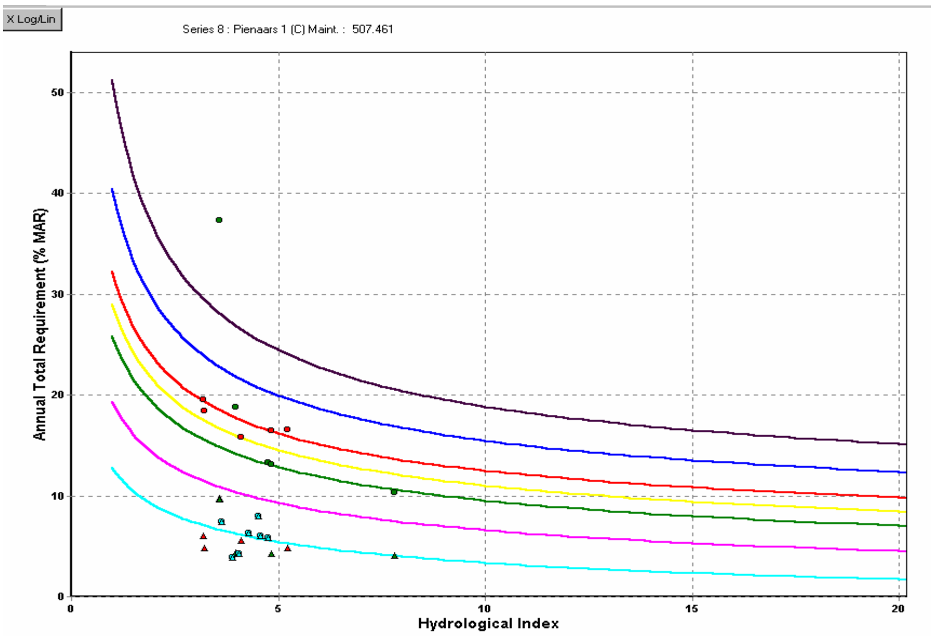


Figure 4.6 Olifants low flow estimation lines after recalibration (refer to text for parameter changes).



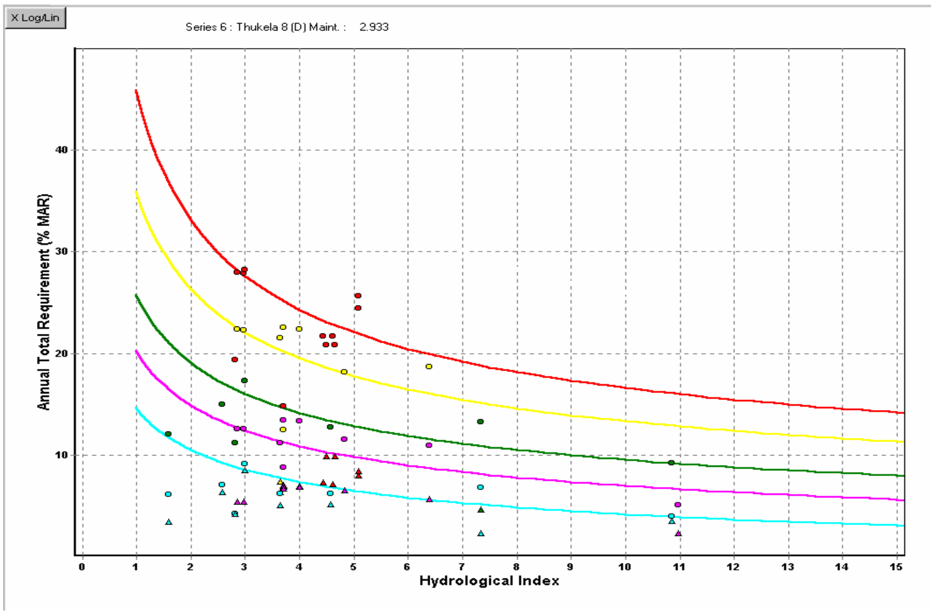
4.6 AN EXAMPLE – RECALIBRATING THE MODEL FOR THE THUKELA CATCHMENTS

The Thukela Reserve determination was undertaken in 2002/03, while some earlier results were available for 1997 and 1998. There are three regions involved in the Thukela basin, N. and S.Natal, as well as Drakensberg. One of the notable aspects of the Thukela determinations was the large volumes specified for maintenance flood requirements. However, some of the bigger floods are too big to be considered as managed flows and arguably they are therefore not part of the managed Reserve. This issue will be re-considered later.

Figure 4.7 Illustrates the situation for low flows (maintenance and drought) before calibration. The main points to note are:

- There is quite a lot of scatter in most of the different categories, but there is no real justification for changing the estimation lines for all categories down to C/D.
- There is, however, justification for lowering the D category and drought line, particularly at the low hydrological index end of the line. Consequently, the parameter MP1 was changed from 0.93 to 0.935 and MP2 from 20 to 17.

Figure 4.7 Default category lines and points for the Thukela sites.



As with the Olifants, there is very little that can be said about recalibrating the high flow estimation lines as there is too much scatter. The only worthwhile observation is that the determinations are substantially higher than the estimation lines. If the large floods are removed, there is still a large scatter but not all the determinations are above the estimation lines. There is clearly a great deal of room for improvement in terms of flood requirement estimation.

4.7 CONCLUSIONS, FURTHER ISSUES AND RECOMMENDATIONS

The SPATSIM approach appears to be highly suitable for storing the information that is generated by quantity Reserve determinations and it is possible that it could be extended to the water quality Reserve in the future. It is very straightforward to transfer data into the system if the Reserve determination team has been using SPATSIM and the models that have been developed to determine Reserves. Even if other methods and tools have been used, it should not prove to be too difficult to generate most of the required information, so that there is a degree of information consistency across all Reserve determinations.

It has been suggested by some critics of the Desktop Reserve model that the %MAR values reflected in some of the diagrams provided in this section of the report are too low.to sustain ecological functioning, particularly for the higher categories (A and B). It is therefore necessary to remind all users that the estimation curves are based on visual 'best fits' to the data that have been derived from a range of ecological Reserve determinations (or IFR studies prior to the revision of the National Water Act in 1998). The Desktop estimates are therefore merely a reflection of the results that have been generated by South African ecological specialists over recent years. The re-calibration software will clearly indicate where results from specific regions or rivers deviate from the Desktop Reserve model estimates and appropriate action can be taken.

The main outstanding issue is how to establish reliable procedures for continued population of the database as more determinations are undertaken by a wide group of DWAF Service Providers. It is also necessary to determine who, or which group, will manage the database and receive all the information. Logically, this should be the RDM Office of DWAF if they have the staff capacity to fulfill this function. There seems to be little doubt that the RDM Office should be the custodians of the database, even if they rely upon outside assistance to maintain it. The RDM Office has the responsibility for recommending Reserves to the Minister and therefore it is important that they have access to the most up-to-date information on a national basis. They are also faced with the task of extrapolating from past determinations to new sites and the Desktop calibration model is designed to assist with that process.

One of the other issues to address is the methods that will be used to disseminate the information in the database to a wider audience to allow others to make use of the experience base that it contains. Clearly some type of web-based procedure would be ideal but it is not immediately apparent how best to achieve this.

The main recommendation is that the RDM Office assume responsibility (either themselves, or through the appointment of a suitable agent) for ensuring that the database is up-to-date and make it the responsibility of all Reserve specialist teams to supply the necessary information at the conclusion of a determination. Guidelines on the required data and its format are provided within this document.

5. FLOW-STRESSOR RESPONSE APPROACH TO ENVIRONMENTAL FLOW REQUIREMENT ASSESSMENT
J O'Keeffe and DA Hughes

5.1 BASIC PRINCIPLES

Globally, methodologies for assessing environmental flow requirements (EFRs) for rivers can be assigned to one of four categories (Tharme, 1996): hydrology-based approaches (e.g. Richter *et al.,* 1997); hydraulic rating methodologies (e.g. Gippel & Stewardson,1996); habitat simulation methodologies (e.g. Milhous *et al.*,1989); and holistic methodologies (e.g. Arthington,1998). Many of these methodologies are reviewed and compared by, among others, Tharme (1996); Arthington & Zalucki (1998); Dunbar *et al.* (1998); and King *et al.* (1999). As environmental flow methodologies have evolved, there has been a move away from a "minimum flow" concept (Stalnaker, 1990) to a recognition of the importance of flow variability in the structure and functioning of riverine ecosystems (Richter *et al.*, 1997). Poff *et al*. (1997) emphasise five aspects of the flow regime which they consider govern the role of flow as a "master variable" that limits the distribution and abundance of riverine species: magnitude, frequency, duration, timing, rate of change.

Recognising the above, the most widely used process for assessing EFRs in South Africa has been the Building Block Methodology (BBM) (King & Louw, 1998), a holistic methodology developed and used since the early 1990s (King & Tharme, 1994; Tharme & King, 1998). The BBM relies on ecologists, fluvial geomorphologists, hydrologists, and hydraulicians to identify a complex of different flow events required for the maintenance of a range of riverine biota and their habitats, as well as biological and geomorphological processes. More recently, an alternative holistic methodology, Downstream Response to Imposed Flow Transformations (DRIFT - Brown & King, 2000), has been developed. It involves an interactive, scenario-based process, addressing the biophysical consequences of progressive reductions in flows and socio-economic links.

The Flow-Stressor Response (FSR) method has been developed (O'Keeffe et al., 2002) as a tool to guide the evaluation of the ecological consequences of modified low flow regimes, based on the principles of ecological risk analysis (ERA) (Suter, 1993), using an index of flow-related stress. The term "stress" has been used in a number of different senses in the ecological literature, causing some confusion. We have therefore been careful to define and use the term as the ecological response to stressors. The reasoning for this is explained in section 5.1.1 below.

The FSR method is designed for use within holistic methodologies such as the BBM and DRIFT, as a way of consistently capturing specialist knowledge on the relationship between flow, hydraulic habitat, and the responses of instream biota. The relationships can then be directly translated into a stress regime for any flow regime scenario, in terms of magnitude, frequency and duration - three of the five critical components of flow suggested by Poff *et al.* (1997). The method is independent of the level of biological knowledge available, although (as with other approaches) this will affect the degree of confidence that can be placed in the flow recommendations.

This section is a description of the FSR and its application to instream biota at low flows. It concentrates on water quantity requirements, but a parallel process is being developed to assess ecological stresses in relation to water quality.

5.1.1 The meaning of 'stress'

"Stress" and "stressor" are terms which are increasingly being used in the ecological literature, particularly in relation to ecological risk analysis, to the extent that the former Journal of Aquatic Ecosystem Health has recently changed its name to the Journal of Aquatic Ecosystem Stress and Recovery. Intuitively, stress is a term which conveys a useful idea about pressure and tension, which most people are able to relate to. In this sense it is similar to terms such as health, integrity and even disturbance, which have been annexed by ecologists to express ecological states which convey important messages to laymen and specialists alike, but which can be quite nebulous in scientific terms, unless they are carefully defined and quantified (e.g. O'Keeffe, 1997; Polls; 1994).

When the term Flow-Stressor Response was first adopted (O'Keeffe et al., 2003), the intention was to capture the idea that changing flows in rivers (and particularly reducing low flows) increases the stress on the riverine ecosystem. This seemed to be at the heart of the philosophy behind environmental flows – that components and processes in the river are placed under pressure and strain as hydraulic conditions change in response to modified flows. It was acknowledged that the natural variability of flows imposes a natural stress regime on the river, and that the undesirability of a modified flow regime should be assessed in relation to how far the stress regime departs from the natural. Stress was defined as follows (O'Keeffe *et al*, 2003):

> "The term *stress* is used ...... to denote the discomfort/damage suffered by the flow-dependent biota as discharges are reduced. Natural flow regimes normally include low flow episodes which cause stress to elements of the biota (equivalent to components of the natural disturbance regime *sensu* Townsend, 1989). Stress is therefore seen as a requirement for the maintenance of the natural dynamic mosaic of species assemblages through space and time, and the severity of stress likely to be caused by any modified flow regime is judged by how much it is increased or decreased from natural levels."

It has subsequently become obvious that the ecological use of the term stress is surrounded by some confusion, summarised for example by Begon *et al* (1996):

> "Physics has a strict definition of a "force per unit area" and producing "strain" in the body to which the force is applied. Biology has a wide variety of meanings .... The word is often used confusingly in two senses, both to describe force and the condition induced in the organism by the force - a confusion of stimulus and response".

A search of the literature confirms that stress is being used both to describe the stimulus and the response. For example, Jooste *et al* (2000) use a definition of stress from Suter (1993): "The proximate cause of an adverse effect on an organism or system" (i.e. stress is the stimulus), but in the same publication they use a definition of stressor from Murray and Claassen (1999) and US EPA (2000): "Any physical, chemical or biological entity or process that can induce an adverse response" (i.e. stressor is the stimulus). This confusion has most probably been caused by the different formal meanings assigned to stress in Physics and Psychiatry. The Physics definition is expressed by Begon *et al* (1996) above, in which the stress is the stimulus, and strain is the response. In the psychiatric definition, the stressor is the stimulus, and the stress (or stress reaction) is the response.

The definition given by Chaplin (1985) in the Dictionary of Psychology is:

"Stress (Noun): A state of strain, whether physical or psychological. Stress test: A real life situation in which the individual is put under pressure while his ability to carry out a task is measured."

Gelder *et al* (1990) clarify the psychiatric meaning of stress further:

> "First it is applied to events or situations .... that may have an adverse effect on someone, second, it is applied to the adverse effects that are induced. …. The first set of factors can usefully be called stressors.….. The effect on the person can usefully be called the stress reaction".

From the above discussion, it is obvious that there is no single meaning for stress that will be correct in all circumstances. Because the term is central to the concept of the FSR method, we have to adopt one clear meaning. We have therefore decided to adopt the psychiatric definition of stress, and to call the method the Flow-Stressor Response method for the following reasons:

- Most of the ecological literature implicitly or explicitly uses the terms in the Psychiatric sense, with stressor used to denote the stimulus or cause, and stress to denote the response. The US EPA (2000) uses stressor in this sense:

  "The Office of Water and Office of Research and Development of the US EPA have developed a process for identifying any type of stressor or combination of stressors that cause biological impairment."

  Jooste and Claassen (2001) also intend stressor and stress to be used in this sense, although their subsequent use is inconsistent:

  "The hazard is a characteristic of the stressor that emphasizes what could happen if the ecological entity is exposed to the stressor." "…. some activities that may cause stress to the aquatic ecosystem". "For a system that is managed to be under constant stress …."

- In the psychiatric sense, individuals have different tolerances to stress. Everyone needs some level of stress in order to operate optimally. Some individuals thrive under conditions of considerable stress, and become bored and unmotivated under tranquil conditions. Others will quickly be overwhelmed by quite mild stressors. In addition, everyone needs periods of tranquillity between periods of stress in order to function best. This sense fits excellently into the concept of ecological stress in rivers. All rivers have a natural disturbance regime, with periods of high flow, periods of seasonal low flow and droughts, and occasional floods. The biodiversity of any river is adapted to this variability, and will change in response to a modified disturbance regime. Flow is one of the main drivers of that regime (e.g. Poff *et al*, 1997). Some rivers, such as temporary streams, are geared to severe changes, and therefore to high levels of stress, in the sense of the FSR method. Others, such as spring-fed streams, may be adapted to a small amplitude of fluctuations, and therefore have a low natural stress regime. It is widely recognised that a regulated increased flow regime which dampens natural disturbances may cause as much change to a riverine ecosystem as one in which flows are reduced by abstraction (e.g. O'Keeffe and de Moor, 1988). In the FSR method, stress *per se* is not seen as undesirable – it is the comparison of the stress regime for any modified flow regime with that for the natural regime that reflects the relative severity of the modification. In this way, the FSR method acknowledges the effects of decreasing stress as well as increasing it.

Because the term is being used extensively in ecological literature, it is suggested in this report that the term stressor should be consistently adopted to denote the stimulus, and the term stress should denote the response. In general, it appears that the terms are being used implicitly in the psychiatric sense, and that this sense should also be adopted consistently. It is also important to recognise that the term stress is being used for abiotic as well as biotic responses (cf the Journal of Ecosystem Stress, and Jooste and Claasen, 2001 above), and this use should also be explicitly recognised.

5.1.2 A description of the Flow-Stressor Response method

The basis of the method is the application of a generic stress index describing the progressive consequences to the flow-dependent biota of flow reduction. Table 5.1 provides an example of such an index (from 0 - no stress, to 10 - very high stress) where the stressors, flow hydraulics and associated habitat changes are related to biotic responses in terms of abundance, life stages, and persistence. The definitions apply to instream fauna (and, therefore, separate ones have to be defined for other components of the biota, such as riparian vegetation), and are calibrated for organisms that would require flowing water conditions for optimal habitat.

The index in Table 5.1 reflects instantaneous or short-term biotic responses. Even sensitive rheophiles seem able to persist during short periods of low or even no-flow (e.g. Chutter & Heath, 1993; Tharme & King, 1998), but may disappear in response to prolonged flow reduction. The longer-term temporal dimension is mainly taken into account when the stress curves are related to hydrological time series, to define stress regimes, by calculating the frequency and duration of different stress magnitudes (described in section 5.4 below).

The process for application of the FSR method is as follows (each of these steps is described in greater detail, with examples, in section 5.4):

- The selected sites of the study river are surveyed and described in terms of hydraulic habitat (depth, velocity, and wetted perimeter) at a range of discharges.
- The generic stress index (Table 5.1) is applied to each site by specialist ecologists, to develop stress-flow relationships for one, or typically more, critical flow-dependent species or groups. The curves describe the relationship between changing discharge and stress.
- Where more than one stress curve is produced, these are integrated to produce a single critical curve, based on the highest stress for any species/group at any discharge.
- It may be appropriate to develop separate stress curves for different seasons, because, for instance, the same magnitude discharge may have quite different stress implications during hot and cool seasons. In such a case, the curves should be used separately to produce seasonal stress profiles.
- Each specialist describes the conditions, for their community/component, which would equate to different ecological categories (ECs). Typically, these conditions are described for one category better and one category worse than the present state category. These conditions are formulated at 4 levels of increasing detail, as an objectives hierarchy – the EC (A to D); general flow characteristics; community objectives; and target species. These conditions or objectives should be described in terms that can be converted to stress levels, durations and frequencies.
- The specialist hydrologist uses the critical stress curve to convert the natural and any other flow time series (e.g. present day or other selected scenario) to a stress time series.
- The resulting stress time series are analysed in various ways to summarise the stress regime in ways which describe the magnitude, duration and frequency of stress levels

experienced by the target organisms for the flow scenarios. Two possible analyses are stress duration curves and spell analysis for the specified stress levels.

- The natural stress regime provides a reference against which to assess the relative changes in biotic stress for the various flow scenarios.
- Specialist ecologists assess the severity of the increases (or decreases) in stress, describe the ecological consequences, and rank the scenarios in terms of their impact. The aim of the ranking process is to identify the scenario for which the stress profile will impose the least additional stress on the biota.
- Because the specialists have defined stress levels, durations and frequencies that equate to a number of ECs (see 5 bullets above), these points can be identified on the scenario duration curves. The points are used as a guide to identify the central tendencies for a number of the ECs. In this way, the specialists can build up a series of bands of conditions which would correspond to each EC.

Table 5.1 (Next page) Flow-Stressor Response generic table for low flows (WP = Wetted perimeter).

Table 5.1 represents an example of a generic index of stress for flow-dependent instream fauna in terms of stressors (defined as reduction in low flow and altered physical habitat) and responses (defined as changes in the abundance of target species; risk to sensitive life-stages; and altered persistence).

NB 1: The stress index relates to instantaneous, or at least short-term levels of stress. The frequency and duration of stresses is built into the analysis process when the stress indices are applied to flow time series.

NB 2: The "Site specific discharge" column is filled-in in relation to hydraulic conditions at a particular site, the flow in the top row relating to the lowest flow at which there will be no risk to the most sensitive flow-dependent organism/component. Each specialist then identifies the flow above which each target organism/component will be at no risk. This flow equates to a zero stress for that target organism/component. Each specialist then identifies the flows at which each target organism/component will experience the response described. Some highly sensitive organisms may disappear at a stress of 7, while some more tolerant organisms will survive to a stress of 9 or even 10. The objective is therefore to identify a range of flows at which a range of organisms/components will experience an increasing risk of reduction in numbers and disappearance.

Footnotes to Table 5.1:

1 *For specific sites and target species, one or more of the hydraulic variables may best reflect changes in stress level. This also applies to "physical habitats". Depending on the type of river channel, the habitats may not always match up to the hydraulics in each row. In these cases, the table may need to be modified to suit local conditions.*

1. *Depth, velocity and WP are the variables that have been chosen for this example table, since these are the most commonly considered descriptors of hydraulic habitat in environmental flow assessments. As the method is tested, it may be appropriate to include other variables (e.g. Froude number, benthic shear stress etc.).*
2. *"Fast" and "deep", and "wide", in this context mean high maximum velocity and maximum depth, and extensive WP, and will be relative to the size and physical structure of the study site. The interpretation will also be in relation to the preferred hydraulic ranges of the target organism(s). The authors have assumed that the structural and resultant hydraulic complexity of most natural river channels ensures that, when there are areas of fast deep flow, there will also be shallow areas of slow or no flow, for instance at the channel edges, and in backwaters (Rowntree & Wadeson, 1996). It can therefore be assumed that habitat remains at suitable flows for most species which do not require (or prefer to avoid) high velocities and depths.*
3. *Physical habitat is addressed in terms of quantity and quality. Quantity refers to the proportional representation of different habitat types by area and number of patches, and "in excess" implies that available habitat exceeds population requirements at the time of the study. "Quality" refers to the diversity and hydraulic connectivity of habitat types.*
4. *The criteria listed in these three columns should be treated as guidelines, which may vary for different river types. For instance, in semi-arid rivers, many rheophilic species may be euryoecious, and able to survive the disappearance of preferred habitats for extended periods (Davies et al., 1994).*
5. *"Rheophilic" is used to denote species which prefer flowing water conditions. "Sensitive rheophilic" is used to denote species which are entirely dependent on flowing water conditions to complete their life-cycle.*
6. *"Healthy" indicates that organisms are in preferred conditions throughout the life-cycle.*
7. *"Viable" implies that the life-cycle is functional, but conditions may be marginal.*

"Persistence" implies at least local presence of the organism(s). Disappearance of populations /species/groups signifies at least emigration from the site, but includes possible local or wider extinction, at temporary or longer-term scales.

Site specific discharge (m^3s^{-1})	[1]Stressors			[5]Biological responses of target organism(s)		
	[2,3]Flow-related hydraulics	[4]Physical habitat	Stress Index	Abundance	Aquatic Life Stages	[8]Persistence
	Very fast Very deep Very wide WP	In excess Very high quality	0	Very abundant	All [7]healthy	Yes
	Fast Deep Wide WP	Plentiful High quality	1	Abund.	All healthy	Yes
	Fast Deep Wide WP, slightly reduced	Critical habitat sufficient Quality slightly reduced	2	Slight reduction for [6]sensitive rheophilic spp	All healthy in some areas	Yes
	Moderate velocity Fairly deep WP slightly/ moderately reduced	Reduced critical habitat Reduced critical quality	3	Reduction for all [6]rheophilic species	All healthy in limited areas	Yes
	Moderate velocity Some deep areas WP moderately reduced	Critical habitat limited Moderate quality	4	Further reduction for all rheophilic species	All [7]viable in limited areas, critical life-stages of some sensitive rheophilic species at risk	Yes
	Moderate/slow velocity Few deep areas WP moderately/ very reduced	Critical habitat very reduced Moderate/low quality	5	Limited populations of all rheophilic species	Critical life-stages of sensitive rheophilic species at risk or non-viable	Yes
	Moderate/slow velocity No deep areas Narrow WP	Critical habitat residual Low quality	6	Sensitive rheophilic species rare	Critical life-stages of sensitive rheophilic species non-viable, and at risk for some less sensitive species	In the short-term
	Slow Shallow Narrow WP	No critical habitat Other habitats moderate quality	7	Most rheophilic species rare	All life-stages of sensitive rheophilic species at risk or non-viable	Most sensitive rheophilic species disappear
	Slow Trickle Very narrow WP	Flowing water habitats residual Low quality	8	Remnant populations of some rheophilic species	All life-stages of most rheophilic species at risk or non-viable	Many rheophilic species disappear
	No flow	Standing water habitats only Very low quality	9	Mostly pool dwellers	All life-stages of most rheophilic species non- viable	Most or all rheophilic species disappear
	No surface water	Only hyporheic refugia	10	Only specialists persist	Virtually no development	Only specialists persist

5.2 ESTABLISHING THE FLOW-STRESSOR RESPONSE RELATIONSHIPS

5.2.1 The ecological basis for establishing Flow-Stressor Response relationships.

Researchers have for a long time been aware that flow in rivers is a (perhaps **the**) major determinant of the distribution and abundance of the riverine biota. In the 1980s ecologists began to get to grips with the characteristics of flow and hydraulics that influence many species. Statzner, Gore and Resh (1988) provided a benchmark discussion entitled "Hydraulic Stream Ecology", with a carefully designed set of samples from rivers in Germany, through which they supported their hypothesis that the distribution of lotic organisms is strongly related to hydraulic conditions. There is now an extensive literature (e.g. Lamouroux *et al*, 1998; Weeks *et al*, 1996) which supports and extends the work of Statzner *et al* (1988).

Organisms may be reacting to complex hydraulic characteristics (such as turbulence in the free flow, and the force of flow prevailing at the stream bed), sometimes at very small scales that are difficult to measure. One of the main contributions of Hydraulic Stream Ecology has been to demonstrate that simple measurements of average velocity in the water column, depth and bed roughness are sufficient to provide quite adequate correlations with the distributions of flow-dependent organisms. This has meant that stream ecologists have been able to characterise the hydraulic habitat preferences of species without the necessity for very high-resolution small-scale studies. As a result, there is now information on these preferences for large numbers of riverine species in many parts of the world, including South Africa. The information is usually collected and displayed in the form employed by Weeks *et al* (1996), and example of which is shown in Figure 5.1.

Once the habitat preferences can be quantified (or inferred where there is no detailed data), it becomes possible to predict the effects of changing flow on the distribution of species. In the FSR method, as with most environmental flow methodologies, hydraulic cross-sections are surveyed and a hydraulic model provides the relationships between water level, discharge, average velocity, depth and substrate inundated. It is then possible to assess how much preferred habitat will be available at different flows. The central assumption in the FSR method is that, as low flows are reduced, this loss of habitat will result in a progressive reduction in the abundance of flow-dependent communities. If flows continue to be reduced, habitat suitability will decline, with a concomitant increase in risk to the more sensitive life-stages of the species. At some point, flow reduction will result in no suitable habitat remaining, and therefore in the eventual disappearance of the species. It is the job of the ecological specialists to be able to:

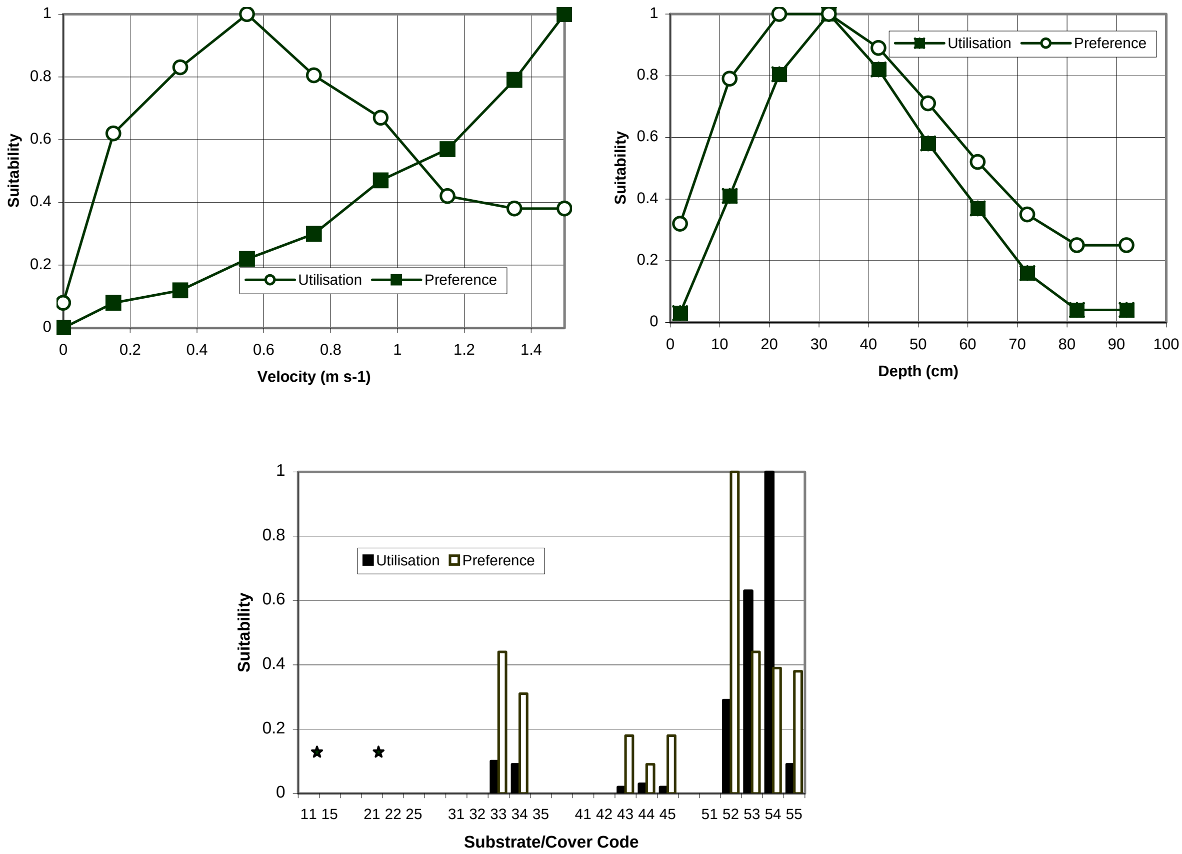
- Identify those species which are most flow dependent
- Quantify the hydraulic characteristics which govern their flow dependence
- Using the hydraulic information provided at each site, relate the reduction in flow to reduced habitat availability for flow dependent species
- Construct a index of increasing stress, according to the generic table (Table 5.1), from which a site-specific relationship between flow and stress is characterised
- Identify objectives or conditions which will result in a species or community achieving one or more ecological states, presently identified as ecological management classes from A to D, where A is natural and D is largely modified. These objectives must be at a level of detail which can be related to stress levels, durations and frequencies. An example of such objectives is provided in Table 5.2.

Once the hydrologist has a relationship between stress and flow, it is a simple matter to convert a flow time series to a stress time series for a species. The hydrologist can then provide the ecologists with information on the range of stresses that will be experienced by an organism over time, and the duration and frequency of each stress level. For any potential flow regime, a stress duration curve can be constructed. The stresses defined in the objectives hierarchies can then be applied to the duration curves to identify what class would be most likely to result (see Figure 5.5).

Converting from species/community stress to ecosystem stress

The main purpose of environmental flows under the SA Water Act is to “maintain the ecological functions on which humans depend” (principle C.3), rather than simply to maintain individual species. The concentration on individual species or communities of fish, invertebrates or plants in all EF methods is because they are the best indicators that we have of the health or integrity of the system. It is also true that it is extremely complex to characterise the functions themselves, or to identify when and how they are changing. It is therefore necessary to convert the requirements for indicator species or communities, to a best estimate of system requirements. Within the FSR method, this is done by combining the initial stress curves for all the indicator species, and identifying the critical curve – that composite flow-stress relationship which shows the highest stress level for any particular flow. Figure 5.2 shows an example. This is a conservative or “precautionary principle way of defining system stress, ie it tries to identify the most sensitive component of the system at any given condition. It would theoretically be possible to allow for a less stringent system requirement by choosing to ignore the requirements of the most sensitive species, and using the flow-stress relationship for “averagely” flow sensitive species. Given the uncertain resolution of our ability to predict the responses of riverine ecosystems to long-term changes, it would be preferable to use the most sensitive species as our benchmark.

Figure 5.1 Hydraulic habitat preferences of the pennant-tailed rock catlet (*Chiloglanis anoterus*) in the Sabie River, depicted in terms of velocity, depth, substrate and cover (graphs re-drawn from Weeks *et al*, 1996).



Footnote: The cover codes (10 to 50) indicate the type of refuge sought – none (10), offstream overhead (20), instream object (30), instream overhead (40) or a combination (50). The substrate codes (1 to 5) indicate dominant particle size where the fish was sampled, from fines and sand (1) to boulder (4) and bedrock (5) according to the Wentworth scale. 295 adult C. anoterus were sampled to construct these curves.

Table 5.2 An example of an objectives hierarchy for aquatic invertebrates for a site in the Molenaars Rivers, Western Cape (from the Breede River Reserve workshop).

Level 1: Overall objective: To maintain an Ecological Reserve Category of B for invertebrates.

Level 2: General flow objectives

Low flows

Category requirements	**Stress**	**Season**	**Dur - % of time**
Maintain higher low flows in winter than in summer. Summer species are adapted to lower flows than winter species	1	winter	70
Maintain higher low flows in winter than in summer. Summer species are adapted to lower flows than winter species	4	summer	70

High flows

Category requirements	**Range / Class**	**Season**	**No of events**	**Freq.**
Maintain a major flood at the beginning of the wet season ie. May/June. The first major flood resets the river to winter conditions, flushing away fine sediments and summer species such as oligochaetes.	25 - 36 Class III	May/ June	1	8:10yrs
Other major floods throughout the wet season	Class III	winter	3	8:10
Maintain small freshes during spring and early summer. Enhance downstream drift of animals and flush out areas of poor quality water accumulated during summer lowflow	Class I	Spring	6	8:10

Level 3: General objectives for the component

Requirements	**Hydraul. / flow**	**Stress**	**Season**	**Dur - % of time**
SASS >140, ASPT>8	Av vel. > .5m/s	<2	Winter	70
SASS >140, ASPT>8	Av vel. > .2m/s	<5	Summer	70
Community to include a large proportion of sensitive taxa such as 3 or more baetid species, Notonemouridae, Leptophlebiidae, Elmidae, Dryopidae, Helodidae & Limnichidae with lower relative abundances of Chironimidae & Oligochaeta.	As above			
Community diversity = *H'* >4 ie. An even distribution of individuals amongst species, reflected low gradient rank-abundance curve.	variable	5-7	All year	10

Level 4: Objectives for indicator species/communities/habitat

Low flows

Category requirements	Hydraul./flow	Stress	Season	Dur % of time
Demoreptus capensis: (riffles). Maintain reasonable abundances	Av vel >.6 m/s	0	wet	50%
Cloeodes sp. (slow flow over sand)	WP >8m	<2	dry	50%

High flows

Category requirements	Size Range (m3/s)	Season	No of events	Freq.
Demoreptus capensis : Encourage drifting and emergence	5-10	winter	3	8:10

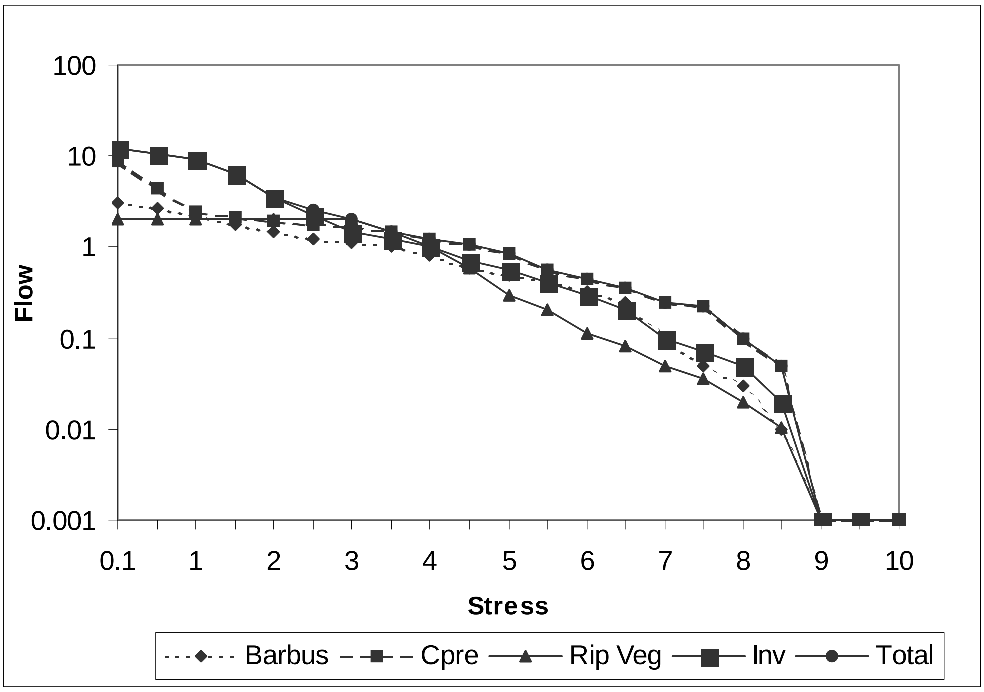


Figure 5.2 Stress/flow relationships for different components of the Blyde River EWR site. The components are two fish species (*Barbus polylepis* - Barbus and *Chiloglanis pretoriae* - Cpre), invertebrates as a group, and riparian vegetation. The line marked "Total" represents the critical stress level for any flow – the highest stress experienced by any component.

5.2.2 Technical Applications within SPATSIM

Figure 5.3 Illustrates the format of the page that is shown when the 'Flow v Stress' option is selected in the Stress/Flow & Risk Indicator Model. For a new application the table of values will be populated with –9 values. The first step is to establish which specialist components are to be used in establishing the critical or 'integrated' Flow v Stress relationship. These can be manually entered in the first row of the table and then saved for future use (use the 'Save' -> 'Var. Names' menu option). The flow values provided by the different specialists for various stress values (0 to 10) are then entered manually in the table, ensuring that at least a value is provide for 0 and 10. Although stress values of 9 and 10 are normally considered to represent no flow, flow values of 0.001 $m^3 s^{-1}$ are often entered to avoid any problems with displaying log values at a later stage. The entered values should then be saved ('Save' -> 'Values' option), before the 'Interpolate' option is selected to fill in the flow values for all stress levels. If the flow values need to be changed, all the interpolated values should be re-set to -9 before interpolating again. The interpolation routine also calculates the critical flow (maximum value across all the components) values at all stress levels.

The results can be viewed using the 'Plot' -> 'Draw' option and saved to either a Windows Metafile or a Bitmap file using the 'Plot' -> 'Save' option. 'Exit' will return the user to the main model page where the other options to calculate stress time series and perform other analyses can be found.

The next step in the procedure is to convert all required time series of flow to time series of stress using the 'Stress T/S' option in the menu on the main model page. It is normal practice to establish the model for a specific site with a reference to SPATSIM attributes containing natural and present day flows as part of the model setup procedure (see section 2.4.2). These can be time series based on daily or monthly data, but all time series used should be generated with the same time step. The stress time series page contains several options (see Fig. 5.4):

- An option to select which component stress-flow relationship to use in the generation of the stress time series (Integrated by default).
- An option to add reference and/or present day time series from different sources other than SPATSIM (usually text files with an .MRV extension and the same format as WR90 flow data files).
- An option to add other time series from various sources including SPATSIM attributes. The normal T/S that will be added are ecological reserve scenarios generated by either the Desktop Reserve or Daily IFR model or time series generated from a separate model (such as the Water Resources Yield model).
- An option to remove existing time series from the analysis.
- An option to save the graph to a Windows Metafile or Bitmap format graphics file.

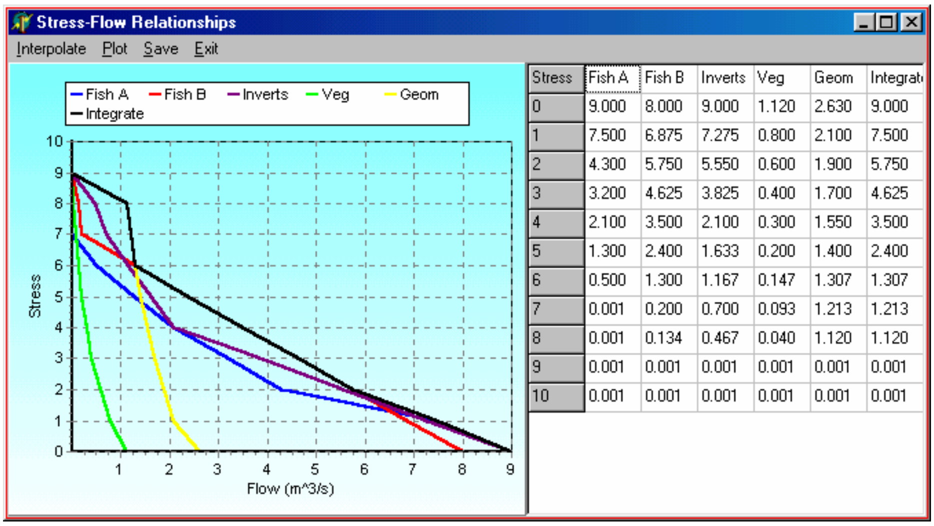


Figure 5.3 Establishing the relationships between flow and stress in SPATSIM

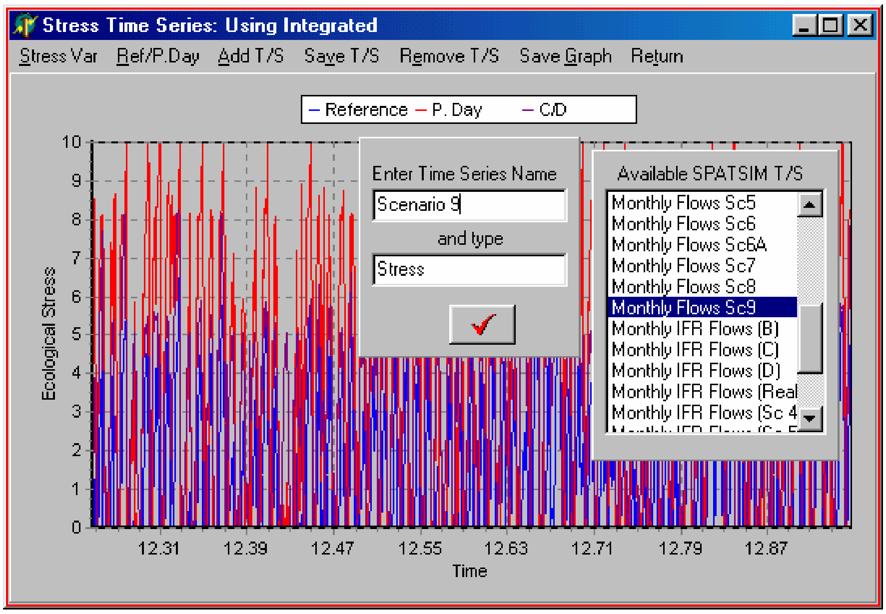


Figure 5.4 The flow time series adding and converting (to stress) part of the flow-stress model of SPATSIM (showing the process of adding a time series from a SPATSIM attribute).

5.3 CALIBRATING STRESS REGIMES FOR DIFFERENT ECOLOGICAL RESERVE CATEGORIES

5.3.1 Calibrating stress regimes using SPATSIM

Figure 5.5 Illustrates the Stress Duration Curve page of the Flow-Stress model, which can be accessed from the front page using the ‘DC Plots’ option. There are various options to change the months used to generate the duration curves, modify the scale of the graph and output the graph to a Windows Metafile or Bitmap format file. While the ‘Run Analysis’ option can also be used to assist in defining suitable stress regimes, the duration curves have proved to be the easiest to deal with and the most informative.

The objective of a stress regime ‘calibration’ is to define the stress characteristics of a specific river that will maintain the river in a specific condition. One of the possible approaches is to generate an initial estimate of the Reserve (or environmental flow) requirement time series using the Desktop Reserve model and default parameters (or the Daily IFR model if all the natural and present day flow data are daily) for a defined ecological Reserve category and compare the converted stress information with the present day and natural conditions. Using the visual information as illustrated in Fig. 5.5, the ecological specialists would then define what levels of stress or greater would be required for specific percentages of time (see further details in section 5.4). It is sometimes easier for the specialists to specify that the river would need to be at a stress level of S or lower for T % of the time to achieve a set of objectives. The X-axis value in Fig. 5.5 is then simply (100 – T).

The parameters or BBM table of the Desktop model can then be modified to reflect the requirements specified by the specialists and a new flow requirement time series generated, converted to stress and displayed as duration curves to check if the results is satisfactory. It is not straightforward to offer guidelines on how to modify the Desktop Reserve model parameters to achieve a specific change in the stress duration curves, but the following information and tips may be useful:

- Remember that high stress equals low flows and *vice-versa*.
- The relationships between stress and flow may be highly non-linear (i.e. a small change in flow may lead to large changes in stress or *vice-versa*). It is therefore frequently a good idea to check what changes in flow are required to achieve the required changes in stress.
- There are various options for changing the parameters of the Desktop Reserve model. The BBM table of flows can be changed manually, the annual values of maintenance and/or drought flows can be changed (retaining the seasonal distribution), the seasonal distributions can be changed (retaining the same annual values) or the assurance rules for the different months can be changed.
- In some cases the type of changes required are easily identified, while in others the non-linearity of the stress-flow relationship makes it more difficult to identify the required changes and several trial attempts are needed to establish the best approach.

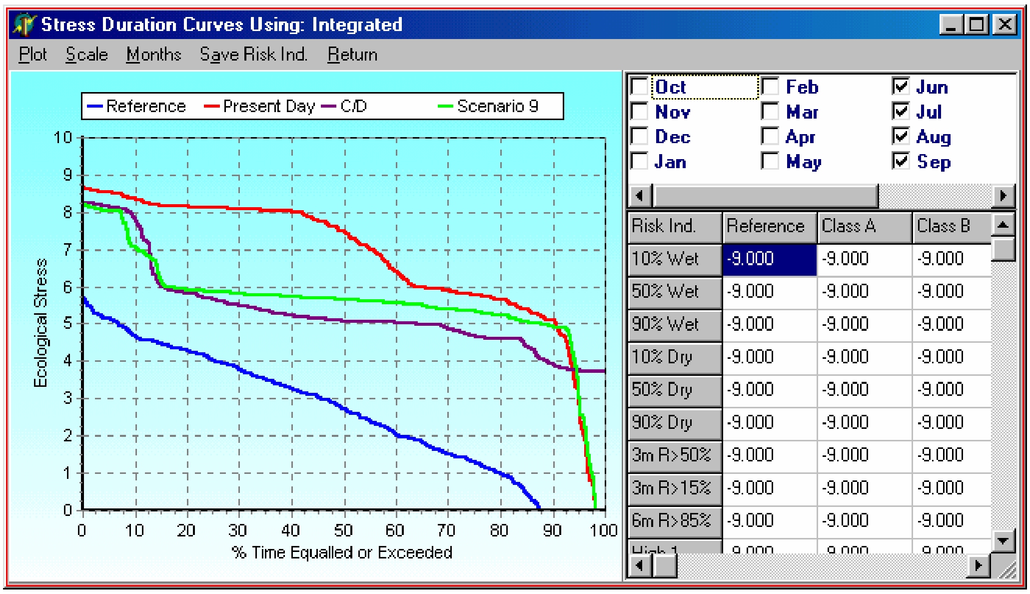


Figure 5.5 Stress duration curve plots based on the data for June to September.

5.4 A STEP-BY-STEP GUIDE TO THE FLOW-STRESSOR RESPONSE METHOD

Step1: The selected sites of the study river are surveyed and described in terms of hydraulic habitat (depth, velocity, and wetted perimeter) at a range of discharges.

This is a standard step in most EF methodologies. An example of a hydraulic cross-section is shown in Fig. 5.6. To enable the specialists to provide greater resolution in their analysis of habitat availability, three dimensional hydraulic habitat modeling is used when resources permit.

Step2: The generic stress index (Table 5.1) is applied to each site by specialist ecologists, to develop stress-flow relationships for one, or typically more, critical flow-dependent species or groups. The curves describe the relationship between changing discharge and stress.

Table 5.1 is a dimensionless index of stress levels, chiefly designed for fish and invertebrates, and may be modified for other communities/components, or for specific applications. Table 5.3 is an example of a table used for riparian vegetation. The specialists should be able to identify, for any section of a river, flows from the hydraulic cross-section which will correspond to particular stress levels. It is not necessary for the specialists to identify a flow for each stress level, but they must be able to provide a range of flows/stresses from which a stress-flow curve or relationship can be drawn up. Table 5.3 is an example for invertebrates at a cross-section in the Mooi River. Stresses of 8, 9, and 10 are simple to pinpoint, since they represent respectively a trickle, no surface flow, and no surface water. In a development of the original concept, Dr Neels Kleynhans of DWAF has elaborated a process for identifying stress levels for fish. The process involves defining slow flow as < 0.3 m/sec, and fast as > 0.3 m/sec, shallow as < 0.5 m and deep as > 0.5 m. From this 4 flow-depth classes can be identified, and the availability of each quantified between 5 (very abundant) to 0 (absent). At the same time, each of the life stages of the target fish species is assigned to a preferred habitat type or types. The flow-depth classes and fish responses are then integrated on a “habitat-flow response and fish species response table” along an index from 0 to 10, which is essentially equivalent to the generic stress index.

Step 3: Where more than one stress-flow relationships is produced, these are integrated to produce a single critical curve, based on the highest stress for any species/group at any discharge.

Each specialist may produce as many stress-flow relationships as they wish to work with, for different species, groups or communities. Depending on the information available and the level of detail required, the invertebrate specialist, for example, may choose to work with the entire community of stones-in-current as one entity, or with a number of different species, genera or families (such as Simuliidae, or Hydropsychidae) which are known to be flow dependent. Each relationship will describe the hydraulic preferences of one such species or group. To identify the sensitivity of the system as a whole, the convention is normally to consider the requirements of the most sensitive component. This requires the construction of a composite, or critical curve, as demonstrated in Figures 5.2 and 5.3 in the previous section. The hydrologist then uses this composite/critical stress-flow relationship to convert the flow time series to stress time series.

Step 4: It may be appropriate to develop separate stress-flow relationships for different seasons, because, for instance, the same magnitude discharge may have quite different stress implications during hot and cool seasons. In such a case, the curves should be used separately to produce seasonal stress regimes.
Where separate seasonal stress-flow relationships are used, the resulting stress duration curves and spell analyses must also be analysed separately.

Step 5: Each specialist describes the conditions, for their community/component, which would equate to different ecological categories (ECs). Typically, these conditions are described for one category better and one category worse than the present state category. These conditions are formulated at 4 levels of increasing detail, as an objectives hierarchy – the EC (A to D); general flow characteristics; community objectives; and indicator or target species. These conditions or objectives should be described in terms that can be converted to stress levels, durations and frequencies.

Table 5.2 is an example of an objectives hierarchy, with stress levels, durations and frequencies attached. These conditions or objectives which will have been identified for three or more classes, are then used to position the stress duration curves for different classes, as described in Step 7, and illustrated in Fig. 5.8 below.

Step 6: The specialist hydrologist uses the critical stress curve to convert the natural and any other flow time series (e.g. present day or other selected scenario) to a stress time series. The resulting stress time series are analysed in various ways to provide summaries of the stress regime which describe the magnitude, duration and frequency of stress levels experienced by the target organisms for the flow scenarios. Two possible analyses are stress duration curves and spell analysis for the specified stress levels. The natural stress regime provides a reference against which to assess the relative changes in biotic stress for the various flow scenarios.

Figure 5.7 shows an example for the Blyde tributary of the Olifants River, Northern province. The effect of the conversion is to invert the time series (but not linearly), since low flows equate to high stresses. Floods are recorded as zero low-flow stress, since the FSR method deals only with low flows.

Step 7: Specialist ecologists assess the severity of the increases (or decreases) in stress, describe the ecological consequences, and rank the scenarios in terms of their impact. The aim of the ranking process is to identify the scenario for which the stress regime will impose the least additional stress on the biota. Because the specialists have defined stress levels, durations and frequencies that equate to a number of ECs, these points can be identified on the scenario duration curves. The points are used as a guide to identify the central tendencies for a number of the ECs. In this way, the specialists can build up a series of bands of conditions which would correspond to each EC.

Figure 5.8 shows hypothetical stress levels identified by several specialists in their objectives hierarchies (see Step 5 above and Table 5.4) in order to position the stress duration curve for a B category. Other points could be identified to position a C or D category. These points will normally assist in the positioning of the central position for a particular categroy, but the category will usually include a range of possible conditions, with a fuzzy boundary where, for example, conditions might be intermediate between a B and C categroy. Because the categories are artificial and largely value judgements, there will always be gradual transitions between them, rather than identifiable thresholds. This concept is best demonstrated in a “traffic light diagram” as shown in Figure 5.9.

In the event that the identified category lines cross, it is necessary for the specialists to check that the results are consistent, and, if they are, to make a careful analysis of the implications. If, in Fig. 5.6 for example, the C line were to be lower at the low % time exceedences than the D line, but higher at the high % time exceedences, this would indicate that very low flows were more important drivers of condition (category) than higher low flows. This might well be the case, for example in a river with highly drought sensitive, but otherwise robust species, but such results would need to be checked carefully.

Table 5.3 A generic stress table used for riparian vegetation, based on the same principles as Table 5.1 – increasing loss of abundance/growth for stresses 1 to 3, increasing risk to sensitive life stages for stresses 4 to 6, and death from 7 on.

	Life history stages / characteristics	
Stress	Adults	Juveniles
0	Complete health and reproductive	Germination and establishment of seedlings
1		
2		
3	First signs of water stress	Growth ceases
4	Flower/fruit abortion	Moderate wilting
5	Leaf wilting or loss	
6	Thinning or partial death of above-ground biomass	Severe wilting
7	Loss or death of above-ground biomass, but rootstock remains viable	
8	Complete death	Dessication / death
9		
10		

Table 5.4 An example of a stress-flow relationship for invertebrates of the marginal vegetation at site 11 on the Mooi River, KwaZulu Natal. Note that flows have only been identified for stresses of 1, 4, and 7, but this is sufficient to extrapolate the stresses between those identified.

Stress Index	**Discharge**	**Flow related hydraulics**	**Physical habitats**	**Abundance**	**Aquatic life stages**	**Persistence**	**Motivation**
1	2,48	Deep wide wetted perimeter 33,93m Max depth 70 cm Ave depth 30 cm Width 29,53 m	Critical vegetation habitat well inundated	All abundant	All healthy	All species	Sufficient marginal veg to house a wide diversity of species
4	0,97	Some deep, wetter perimeter slightly reduced 25,13m Max depth 54 cm Ave depth 22 cm	Critical vegetation bases only inundated	Limited numbers	All viable	All species	Only enough habitat to support a small population which would be at risk
7	0,73	Shallow, reduced wetted perimeter 20,13m Max depth 50 cm Ave depth 20 cm	No vegetation habitat	Most taxa reduced	Some sensitive species at risk	All species persist in the short term	No vegetation habitat but most species will survive in the short term on alternative substrates

Figure 5.6 A typical example of a hydraulic cross-section, surveyed at a number of flows to provide modelled information on discharges, average velocities, depths, and wetted perimeters for a range of water surface elevations.

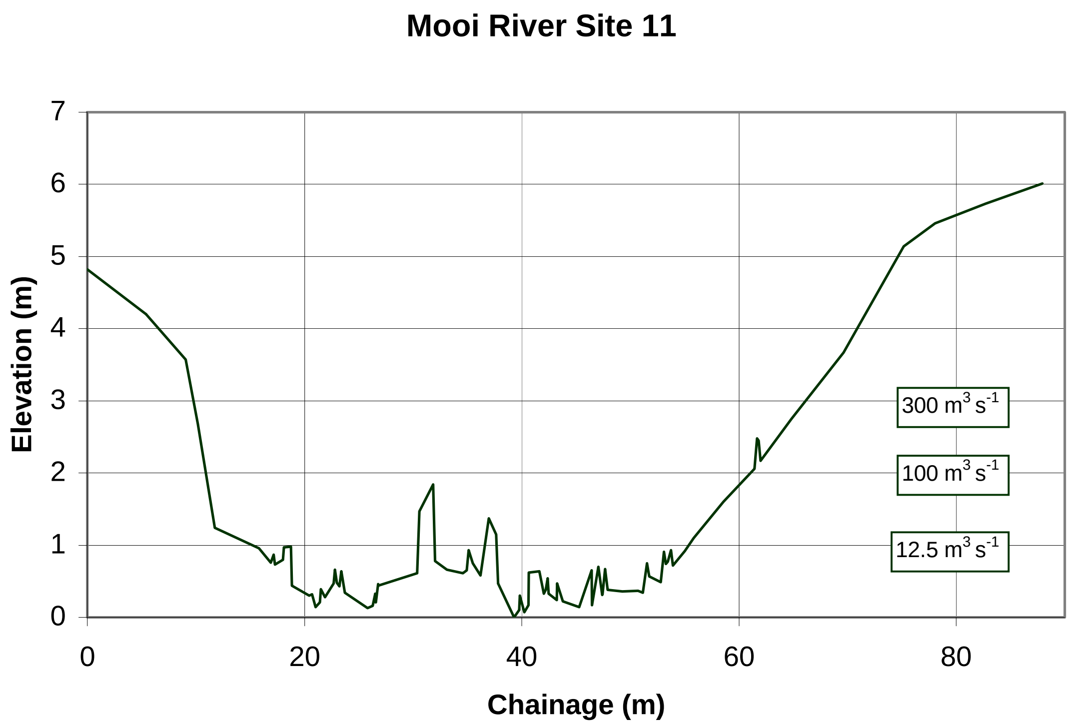


Figure 5.7 The conversion of a natural flow time series from the Blyde River to a stress time series. The results can then be converted to a stress duration curve, shown below as the black line (or see Fig. 5.5). The blue line represents present day use and the red line as the eventual recommendation for an environmental flow regime.

Figure 5.8 A hypothetical example of the application of the stresses identified in the objectives hierarchy, to a stress duration curve to identify the central tendency of a B class. Other classes might be similarly identified in the positions shown.

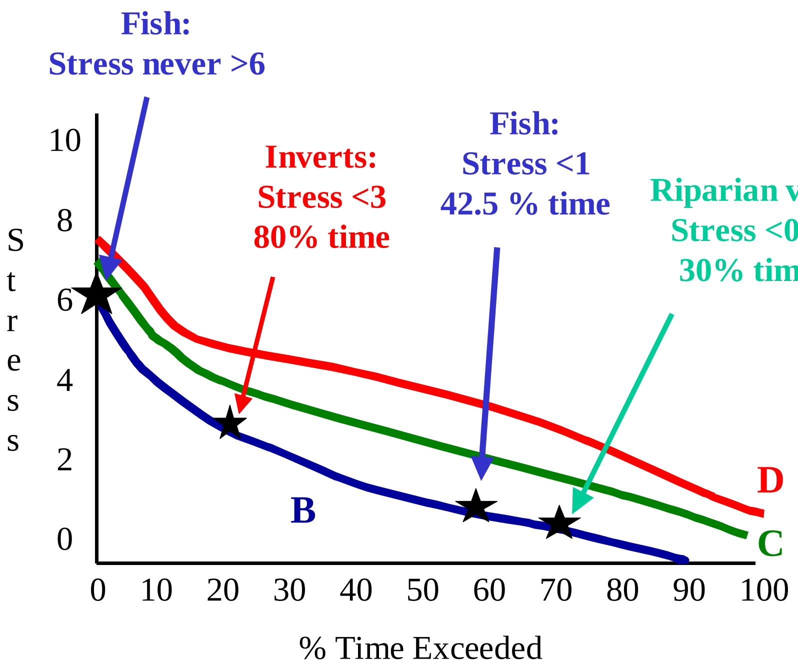
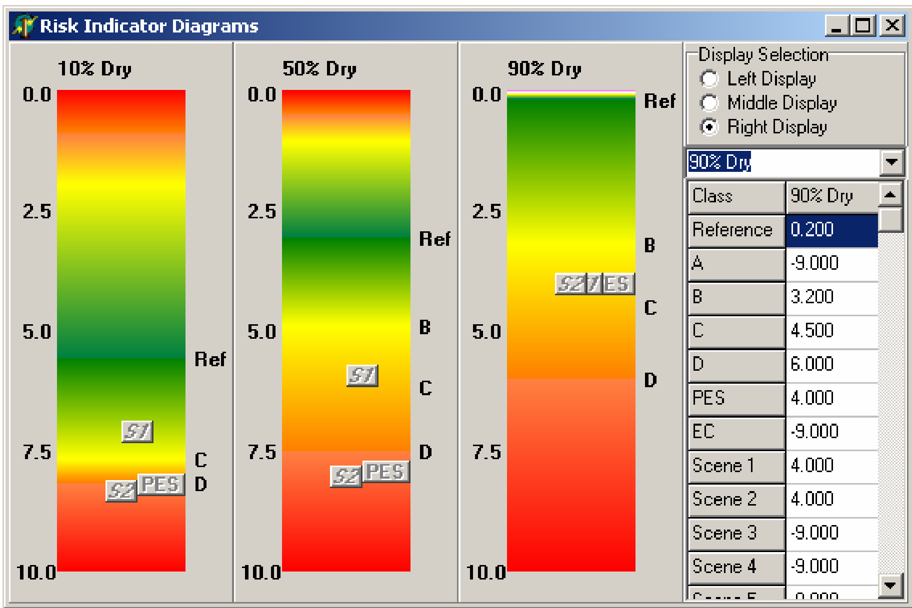


Figure 5.9 A "traffic light" diagram for site 4 on the Thukela River, KwaZulu Natal. The diagram shows the positions of classes B, C, and D related to stress levels (0 to 10) at three % points on the duration curve (10%, 50%, and 90%).



5.4 MORE RAPID METHODS AND HIGH FLOWS - A WAY FORWARD

The application of all comprehensive Reserve determination methods is data intensive and requires a substantial time input from several specialist scientists. This makes the process time consuming and expensive, a situation that has come in for a great deal of criticism from some quarters. However, it should be recognised that in the absence of existing data and conceptual understanding of the ecological functioning of a specific river and the relationship between the functioning and changes to the flow regime, expensive studies are necessary to generate results in which confidence can be placed.

The two critical components of the FSR method are:

- Determining the relationships between flow and stress (which involves a knowledge of the hydraulic cross-section characteristics and the habitat availability at different levels of flow).
- Determining the stress regime characteristics (durations at different stress, stress run characteristics, etc.) that can be considered appropriate to various levels of ecological functioning (i.e. ecological category).

These are essentially the components that require the most amount of data, expertise and time. Therefore any developments in the methodology that seek to reduce the time and costs of application should focus on these components. It seems to be a reasonable assumption that the relationships between flow and stress will be dependent on regional factors affecting the biota that would be naturally present in the system, as well as the site specific factors that are primarily related to the channel geomorphology (cross-sectional shape, longitudinal profile, substrate material and sediment dynamics). Most of these factors are expected to be covered by one or more levels of the Ecoregional Classification System being developed for the whole country (Kleynhans, et al., 2004). It therefore seems logically possible to be able to specify generic relationships between flow and stress for different ecoregions that can be scaled for a specific site on the basis of limited field surveys focusing on the channel characteristics. While this information is not currently available and resources would be required to develop such relationships, the benefits in terms of reducing the costs of Reserve determinations in the future should justify the initial investment. It would be necessary to provide some indication of the confidence that could be expressed in the results of applying such a generic approach and it seems likely that this would vary from region to region.

While the previous paragraph refers to the development of generic flow-stress relationships, it seems reasonable to suggest that this approach could also be applied to the development of generic guidelines for specifying stress regime characteristics (relative to natural) suitable for different levels of ecological functioning.

This whole section has dealt with low flow stress and currently it has not been possible to reach consensus on a suitable approach to applying the same principles to high flows. The consequence of this is that the low and high flow components of a Reserve determination using the FSR approach are not well integrated (a similar approach to that used in DRIFT is normally applied for high flows). This has not proved to be a major problem, partly because low and high flows have always been treated fairly separately and are certainly managed in quite different ways. However, it is not an ideal situation and it would be an advantage to be able to integrate the two approaches in the future.

One of the suggestions made during the course of this project is that up to six high flow groups should be defined (by a limited range of peak flows) on the basis of the functions that they perform with respect to ecological or geomorphological functioning. The basis of assigning ‘stress’ values would then be the frequency with which events in each group occur within each season of the year. For example, in a river where naturally high flow events occur quite regularly (parts of the Thukela catchment, for example), moderate flow events might be expected on average 5 times in the wet season and such a frequency may be associated with a low stress value. If fewer, or more, events occur the stress would be expected to increase for that season. The concepts are similar to low flows, in that both and low and high stress values are expected in the natural situation and a Reserve determination analysis would look at deviations from natural. However, there are still a number of conceptual issues that have inhibited the development of a suitable approach:

- The meaning of 'stress' would vary across the various groups of flow events and this has caused confusion amongst the specialists who have been involved in discussions about the development of possible techniques. For example, within the highest flow group, which are normally designed to ensure geomorphological channel maintenance, 'stress' would be related to changes in sediment dynamics and cross-sectional shape. Within some of the lower flow groups, 'stress' could be related to the functioning of fish breeding cycles or the health of riparian vegetation.
- Within the low flow procedures, 'stress' is estimated from flows on an instantaneous basis and then the time series of stress are analysed for frequency and run characteristics. The situation is more complex for high flows because of the need to account for medium to long term 'memory' in the determination of the 'stress' time series. This is particularly true for the larger events that would not be expected to occur every year. Part of the estimation of 'stress' would then need to include the number of years that have passed since such an event did occur. If a 1:5 year flood does not occur in a particular year that does not constitute high 'stress'. However, if such a flood has not occurred for the last 20 years, it is assumed that the 'stress' is now very high.

There are other problems that are less easy to articulate that have also inhibited the development of a suitable method. The conclusion is therefore that while the application of similar 'stress' concepts to high flows looks attractive, it has not been possible to overcome the conceptual difficulties. It is also reasonable to suggest that there has not been a very high degree of urgency as the existing methods are able to provide acceptable answers.

WATER QUALITY IN THE ECOLOGICAL RESERVE

CG Palmer, WJ Muller & DA Hughes

6.1 METHODS FOR ECOLOGICAL RESERVE ASSESSMENTS WITHIN A DECISION SUPPORT SYSTEM (DSS)

South African water law and policy has undergone fundamental review over the past decade, and one of the new fundamental principles is that of sustainability (DWAF 1997, National Water Act No. 36 of 1998). The concept of sustainability implies, long-term, maintenance of ecosystem biodiversity, structure, and function, and delivery of ecosystem goods and services (Palmer et al. 2002). Sustainability requires people to undertake research and to make decisions in the space where economic, social and environmental domains intersect (Fig. 6.1). The concept of the ecological Reserve has emerged from the environmental domain. The ecological Reserve comprises descriptions and quantitative definitions of the structure, water quality, and water quantity required by aquatic ecosystems to maintain a defined level of ecosystem health. Implementation of the ecological Reserve will require taking account of relevant social and economic factors. RDM (resource directed measures) and SDC (source directed controls) are further discussed in the text, and this chapter describes water quality methods within RDM.

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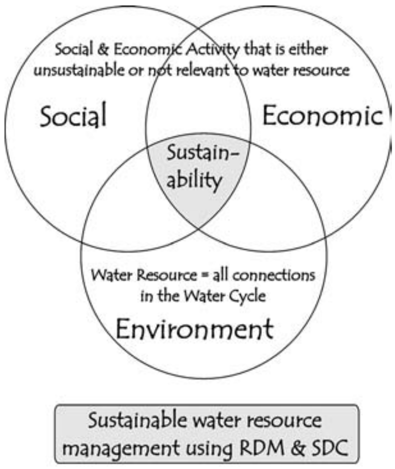


Figure 6.1 The concept of the ecological Reserve.

The National Water Act (NWA) (No. 36 of 1998) recognizes that water resources are in fact ecosystems (rivers, wetlands, lakes, dams, estuaries, and groundwater). These ecosystems offer people a range of free goods and services including water supply, waste dilution, transport, and processing, supply of natural products, nature conservation and biodiversity, flood control, recreation, beauty and places for spiritual activities. The NWA provides for the protection of aquatic ecosystems so that they can go on offering their goods and services to future generations. The Act provides for two mechanisms to manage water resources in South Africa and to ensure resource protection and use at an appropriate level: Resource Directed Measures (RDM), which focus on defining objectives for resource condition and include the ecological Reserve; and Source Directed Controls (SDC) which focus on controlling impacts and include license criteria for both water abstraction and waste discharge.

Implementation of the ecological Reserve requires numerical and descriptive cues, or trigger values, that indicate a change of ecological condition. The concentration that acts as an indicator of a change of condition can be termed a trigger value (ANZACC 1992), a threshold of probable concern (TPC) Rogers (1999), or a boundary value (Appendix 1). A classification system specifying descriptions of classes of ecological condition is being developed, and the currently used classification categories are illustrated in Fig 6.2.

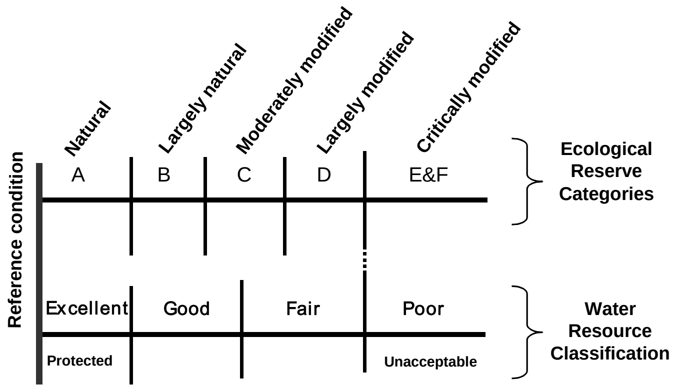


Figure 6.2. A diagram of the alternative classification systems currently in use in ecological Reserve assessments.

The development of methods for quantifying the flow requirements of river ecosystems preceded methods for quantifying water quality requirements (King and Louw 1998, Scherman et al 2003). This was partly because flow is a single factor whereas water quality includes a multiple set of variables. Ecosystem requirements in terms of water quality variables have been internationally approached through the development of protective ecosystem guidelines (DWAF 1996, ANZECC 1992, CCREM 1987). The guidelines aim to prove a trigger value, or concentration that will indicate a move away from the protection of 95% of aquatic biota. The trigger values for a suite of toxic variables that are listed in the DWAF (1996) Guidelines for the Protection of Aquatic Ecosystems, are used as ecological Reserve class boundary values.

In 1999, the first ecological Reserve assessment to include an assessment of water quality was initiated in the Olifants River (Mpumalanga/Gauteng), and methods were developed rapidly during that process (DWAF 2000). Since then, method development has proceeded both through funding by the Water Research Commission (Malan and Day 2002, Palmer et al. in prep.) and through partnerships with the Department of Water Affairs and Forestry during the implementation of ecological Reserve determinations (Scherman – Thukela; Rossouw - Breede)

This report presents the most up to date record of the development of methods for quantifying and describing the water quality aspects of ecological Reserve assessments. All the methods recorded have been developed, applied, refined and discussed by an inclusive group of researchers and water resource managers. Further, the methods for investigating water quality variables have been integrated into the spatially-based decision-support model SPATSIM.

6.1.1 Environmental Water Quality (EWQ)

Traditionally, the term "water quality" has meant water physico-chemistry. It has become increasingly clear that within the ecological Reserve context water quality is more than this, and we suggest an integrated approach termed "environmental water quality" (EWQ) (Palmer et al. in prep.).

The EWQ approach involves understanding how the chemical, microbiological, radiological and physical characteristics of water (water quality) link to the responses of living organisms and ecosystem processes (environment). The primary abiotic factors that shape aquatic ecosystems (water quality, flow, and physical structure) provide the conditions for the biotic processes. These combined bio-physical processes link to social and economic processes through the human use of water resources.

Three components of EWQ

More than one approach is needed to understand the complex interactions in an aquatic ecosystem. There are three main kinds of information that contribute to an integrated EWQ picture:

- information about the physico-chemistry of the water – gained through a chemical and physical analysis of the water
- information about the presence, absence and abundance of biota in the ecosystem – gained through biomonitoring
- information about the responses of specific biota to specific concentrations of chemicals or mixtures – gained through ecotoxicology

Water physico-chemistry

The many physico-chemical variable have been grouped (DWAF 1996) as:

- system variables are generally characteristics of particular sites or regions (temperature, pH, dissolved oxygen concentration, total suspended solids (TSS) and total dissolved solids (TDS) - which includes inorganic salts and ions)
- nutrients (phosphates, nitrates and nitrites)
- toxic substances (metal ions, ammonia, pesticides and herbicides).

Monitoring

Physico-chemical monitoring has been the international norm in pollution control, and provides the data most often used and understood by water resource managers and users. The chemical composition of effluent streams, whole effluents, and receiving waters is measured and analysed on a regular basis. Most trigger values have been provided in terms of chemical concentrations.

South Africa has a national network of water quality monitoring sites. These were historically selected to meet the pollution control requirements of the 1956 Water Act and were mainly located upstream and downstream of point sources. They were not located so as to characterise the natural water quality of aquatic ecosystems. These data, kept on DWAF water quality databases, have limitations, such as:

- sampling is generally monthly and extreme events may be missed and there is therefore a limited capacity to monitor the frequency and duration of interim concentrations
- water quality monitoring sites in rivers are often at the outflow of dams rather than instream. The chemical character of the river water may be different from that of the dam
- wetland water quality is seldom monitored

- the data record may be short or interrupted
- a limited range of variables is measured (some ecologically important variables, such TSS and organic toxins, are normally not measured).

Despite these limitations, the water quality monitoring records are the best data source available to characterise the historical and present water quality, and are more comprehensive than in many other countries.

Links between physico-chemistry and biota: tolerance limits.

Organisms respond to physico-chemical concentrations and magnitudes, and have both tolerance limits and preferences. Species will only be abundant within a specific tolerance range, will be less abundant at the tolerance range boundaries, and will not survive beyond the boundaries. (Within the tolerance limits, biological interactions such as competition and predation also affect abundance and distribution.) Near tolerance limits, organisms use more energy coping with the stress of poor conditions, will have less energy available for essential activities like feeding and reproduction, and may be more vulnerable to competition and predation. The ability of an organism to live and compete effectively is termed fitness. Low, or even undetectable concentrations, pollutants can affect fitness. Low concentration effects that do not kill, but affect performance, are known as chronic effects. These chronic effects influence the relative abundance and composition of aquatic biological communities. Short-term high concentrations cause more immediate acute effects. The presence, absence, abundance and tolerances of organisms provide the links between water physico-chemistry and biotic responses.

Biomonitoring.

The plants, algae, invertebrates, and fish that make up aquatic biota are always in the water, at least for the aquatic stage of their life-history. They experience the cumulative results of all chemical interactions, and the full frequency and duration of extreme chemical concentrations. They respond to the whole integrated chemical condition. If the chemical conditions are favourable, biota have the potential to thrive. If chemical conditions approach or exceed their tolerance limits, they will diminish or disappear.

Biomonitoring is based on the fact that organisms have varying tolerance levels. In any ecosystem, the presence or absence of sensitive organisms, or simply a change in community composition, can indicate the effects of changed water chemistry, which may not be detected by the chemical data record (organisms would respond to a damaging effluent discharged between monthly chemical monitoring.)

Invertebrates, fish, algae, the riparian vegetation and the geomorphology can all be monitored to assess aquatic ecosystem health (Uys et al., 1996, Hohls 1996, WRC 2001, 2002, 2003, Dallas 1997). Invertebrates are often the most useful because they are numerous, and they have a wide range of tolerances. Invertebrates also have the advantage of being mainly sedentary, and remaining in one area. Fish are also useful indicators of pollution, but they are fewer, larger, and generally respond negatively only to higher concentrations. Being mobile, they can swim away from temporarily unfavourable conditions. In South Africa, biomonitoring has only been routinely used relatively recently, even though aquatic biomonitoring methods were pioneered here more than 30 years ago (Chutter 1972, 1998). The systematic River Health Programme, which runs in many parts of the country, relies on biomonitoring. Currently, efforts are underway to extend the methods of biomonitoring rivers to monitoring of other aquatic ecosystems (Mangold, 2001).

Some of the rapid bio-assessment methods, such as the South African Scoring System (SASS), can be undertaken by people with fairly basic training. There are also new biomonitoring methods emerging which allow invertebrates to be rapidly identified to the equivalent of species level, and which measure a more sensitive response (Palmer and Davies-Coleman 2004). Biomonitoring techniques can and do provide a real-time, integrated indication of how biota are experiencing the chemical environment.

Ecotoxicology.

Ecotoxicology is the study of the effects of chemical solutions and mixtures on living organisms. Selected organisms, or communities of organisms, are exposed to single substance solutions or complex mixtures, in the laboratory. The concentrations are carefully controlled and responses are reported as statistical probabilities.
Ecotoxicology provides a quantifiable, causal link between the chemical concentrations that are routinely monitored in water resources and the instream biological responses that are now being increasingly monitored. An understanding of these causal links can assist resource quality managers in setting RQOs, and also help water resource users to meet end-of-pipe licence requirements and instream RQOs.
Ecotoxicology is used world-wide. Test results have been used to set water quality guidelines for aquatic ecosystems in the USA, Canada, Australia, New Zealand, Europe as well as South Africa (ANZECC and ARMCANZ 2000, AQUIRE 1994, CCREM 1987, DWAF 1996). It is also used to set instream criteria and end-of-pipe criteria in the form of toxicity endpoints.

6.1.2 EWQ in ecological Reserve assessments

During a comprehensive ecological Reserve determination, the boundary values between the excellent, Good, Fair and Poor ecosystem classes, for each of a specified range of water quality variables, are determined. This process relies on the physico-chemical data-base, and ecotoxicity test results (both international and local). Response variables, including algal growth and biomonitoring indices are measured and related to the classification system. The whole process is strongly based on an EWQ approach.

6.1.3 Undertaking an ecological water requirements (rivers) assessment for water quality

The protocol for undertaking an ecological water requirement (EWR:Rivers) water quality assessment is described in detail elsewhere (within the SPATSIM help system, as well as on the Ninham Shand website at http://projects.shands.co.za/hydro/hydro/wqreserve/main.htm). The following section describes the data analysis process necessary to complete an EWR (rivers) assessment for water quality. This step-by-step list is a summary of the detailed descriptions provided in Appendix A to undertake assessments for individual water quality variables and these analyses are undertaken in SPATSIM.

Step1: Obtain relevant water quality data and import to SPATSIM.

- SPATSIM assumes that data are obtained from DWAF and the programme has been designed to analyse data obtained in this format.
- An Ecological Water Requirements (Rivers) assessment requires that all available water quality data are assessed for inclusion in a Reserve study. However, not all monitoring point data are suitable or appropriate for inclusion in an assessment: sampling frequency, knowledge of the catchment and professional judgement is used to assess whether data from particular monitoring points are to be included.
- It is important to include monitoring points in all quality resource units.
- Water quality data required to undertake a reserve assessment are:

    - Ca, Mg, K, Na, Cl, SO_4, NH_4, NO_2+NO_3, PO_4, pH, Dissolved Oxygen, Turbidity, Temperature, Toxic substances (listed in the South African Water Quality Guidelines for Aquatic Ecosystems, including toxic metal ions, toxic organic substances, and/or substances from a chemical inventory of an effluent or discharge), Biological indicator data (e.g. SASS data), Chlorophyll a (phytoplankton and periphyton data) and toxicity test data.
    - Not all the above listed data will be available for all water quality monitoring points.
    - Not all water quality variables are obligatory for an EWR: Rivers study.
    - Although not a requirement for comprehensive Reserve assessments, it may be useful to obtain conductivity (EC; mS/m) and Total Dissolved Salt (TDS; mg/ℓ) data.
    - It may be appropriate to include water quality data from dams, especially if water samples are taken from the outflow of the dam.
- Inevitably there are concentrations which are recorded as below detection limits (denoted by a "<") and these should not be considered missing data. These need to be removed from the data record. Statistically, it is deemed appropriate to convert these data to to half the detection limit value.
- Total Inorganic Nitrogen (TIN) values need to be calculated.
- Individual salt concentrations (obtained by reconstituting ion data) need to be calculated. This method is still under development and is not yet available in SPATSIM.

Step 2: Ascertain which monitoring points and relevant data are to be used for Reference Condition assessment and which data are to be used for Present Ecological State assessment:

- Ecological Water Requirements (Rivers) assessments for water quality require that an assessment be made of Reference (unimpacted) condition. This is to benchmark the default boundary values provided in the methods (Appendix 1) for the categories and determine whether natural background levels are different from those values provided. In the event that they are, the values in the benchmark tables need to be recalibrated so that an accurate assessment of the Present Ecological State can be undertaken.
- Data obtained from DWAF water quality monitoring points are used to determine both Reference Condition and Present Ecological State. The confidence level of the assessment is determined by the sample size and the method describes a statistical procedure to calculate this.
    - Data obtained from DWAF water quality monitoring points which have been operational for several decades may be appropriate for Reference Condition assessment. This can be ascertained by plotting the concentrations of appropriate water quality variables over time and determining whether there is a detectable trend over time. If there is a trend, the earlier part of the record may be appropriate for Reference Condition determination (i.e. pre-impact data) while the more recent data record may be appropriate for a Present Ecological State assessment.
    - There may be a water quality monitoring point upstream of any impacts in the resource unit which may be suitable for Reference Condition assessment. In this case, the more recent data record can be used.
    - Assess whether it is necessary, and appropriate, to use water quality data from dam outflow.
    - Although not specified by the method, box-and-whisker plots of monthly medians, 25% and 75% of selected water quality variables provide a useful visualization of seasonal changes, and provides the necessary information required for flow-concentration modelling.

Step 3: Undertake the necessary calculations and analyses:

- Table 6.1 provides a summary of the water quality variables used in an Ecological Water Requirements (Rivers; EWR:Rivers) assessment and lists the analyses to be undertaken.
- Table 6.2 provides a summary checklist for the overall process.

Step 4: Report results:

- It is important that all procedures, results and scientific decisions are recorded for future reference. Appendix 2 provides an example of recording results for an EWR: Rivers.

Table 6.1 Water quality data requirements to undertake the water quality component of an EWR (Rivers) assessment. (*indicates that the variable is optional)

WATER QUALITY VARIABLES	**REFERENCE CONDITION**	**PRESENT ECOLOGICAL STATE**
Inorganic salts:		
Data: Ca, Mg, K, Na, Cl, SO_4 **Calculate inorganic salt concentrations:** $MgSO_4$, Na_2SO_4, MgCl, $CaCl_2$, NaCl, $CaSO_4$ **Data analysis:** $MgSO_4$, Na_2SO_4, MgCl, $CaCl_2$, NaCl, $CaSO_4$	Calculate 95% of reference data.	Calculate 95% of present state data.
	Compare to default boundary table.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
Nutrients:		
Data: NH_4, NO_2+NO_3, PO_4 **Calculate TIN** (NH_4+NO_2+NO_3) **Data analysis:** TIN and SRP	Calculate 50% of reference data	Calculate 50% of present state data
	Compare to default boundary values	Compare to relevant boundary table
	Recalibrate boundary table if necessary	Assign category. Adjust accordingly using Chl-*a* data. Calculate confidence level.
System variables:		
DO	Calculate 5% of reference data	Calculate 5% of present state data
	Compare to default boundary values.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
pH	Calculate 5% and 95% of reference data.	Calculate 5% and 95% of present state data.
	Compare to default boundary values.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.

Turbidity*	Method not yet developed.	Method not yet developed.
Temperature* **Data:** If no water temperature available, calculate daily water temperature from air temperature	Calculate monthly 10% and 90% of reference data.	Calculate monthly 10% and 90% of present state data.
	Calculate the upper and lower boundaries of the categories.	Compare to boundaries obtained for reference condition.
	Summarize results in benchmark table.	Assign category. Calculate confidence level.
TDS / EC	Method under development.	Method under development.
Toxic substances:		
Data: NH_3 (calculate from NH_4 data), Al, As, Atrazine, Cd, Cr, Cu, Cyanide, Endosulfan, F, Pb, Phenol, Hg	Calculate 95% of reference data.	Calculate 95% of present state data.
	Compare to default boundary table.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
Biological response variables:		
SASS **Data:** SASS scores and ASPT scores	Assess whether ASPT score from Reference site is >5% different to default Natural boundary.	Compare ASPT scores from resource unit with relevant boundary table.
	Recalibrate boundary if necessary.	Assign category.
CHL-*a** **Data:** Phytoplankton (μg/ℓ) and periphyton (mg/m^2)	Calculate 50% of reference data	Calculate 50% of periphyton data and mean of phytoplankton data.
	Compare to default boundary table.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
Toxicity	Method not yet developed.	Method not yet developed.

Table 6.2 A summary checklist of procedures to be undertaken in an Ecological Water Requirements (Rivers) assessment of water quality (Details in Appendix A).

Obtain data for Reference condition assessment	
• Undertake trend analysis (per water quality variable) to assess whether data record appropriate for Reference Condition assessment	
• Undertake necessary calculations to assess whether benchmark boundary value tables need recalibrating	
• If no recalibration necessary, proceed to Present Ecological State assessment	
• If recalibration necessary, perform necessary calculations for recalibrating boundary values before proceeding with Present State assessment	
Obtain data for Present Ecological State assessment	
• Undertake analysis for Present Ecological State assessment per water quality variable	
• Assign category per variable	
• Calculate confidence levels.	
Overall water quality category	
Record and report relevant information (see Appendix 2 for an example of how to present results in an Ecological Water Requirements: Rivers report)	

6.2 TECHNICAL APPLICATIONS WITHIN SPATSIM

While the facilities within SPATSIM that are available to support the determination of the water quality component of the Reserve are not fully developed some facilities have been added to import the required water quality data into a SPATSIM database application and undertake some preliminary data analyses.

6.2.1 Importing water quality time series data

DWAF have a standard water quality data format that includes all the data (where present) in a text file with very long lines. One of the standard time series data import routines included within SPATSIM allows individual water quality components to be imported into a time series data attribute (Fig. 6.3). The data files must have at least 1 header line (to identify the data components that are present and to determine the position of the data within each line of the text file) and the user can specify the component required and what to do in the case of data marked with the ‘<’ symbol (i.e. below the range of measurement).

6.2.2 Water quality data analysis model

This is an external application within SPATSIM (see also Section 2.4.2 of this report and the SPATSIM help) that is being developed to support the determination of the water quality Reserve. Some aspects of this procedure are still being finalised (Jooste, pers. comm.) and therefore it has not been possible to complete the development of the software ate the time of writing this report. However, the model will be completed as soon as the procedures and algorithms are finalised. At this stage, the model provides a facility for statistically summarising the available water quality data, setting the date range of the data to be used in later analyses and estimating the salt concentrations from the raw water quality data.

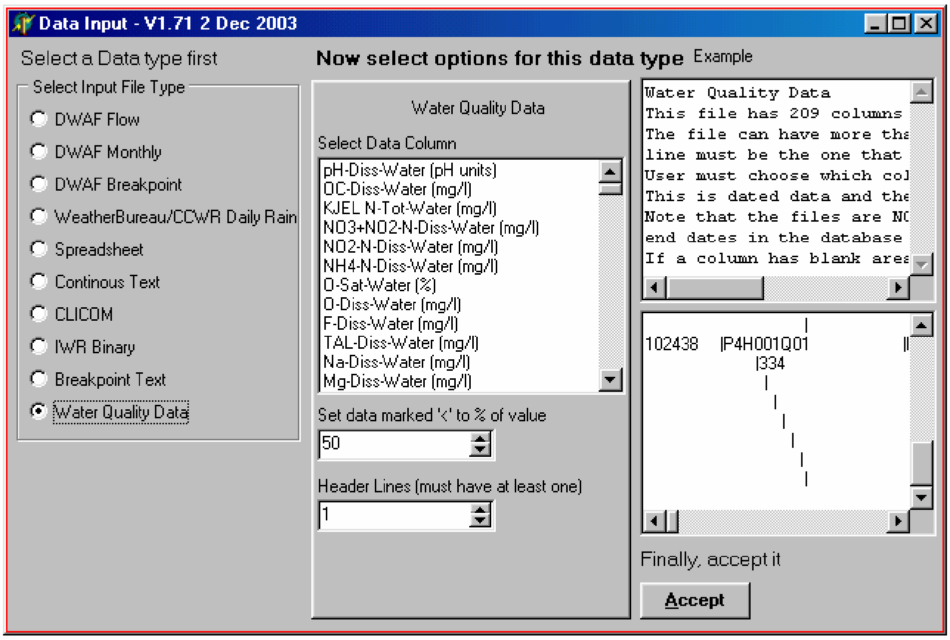
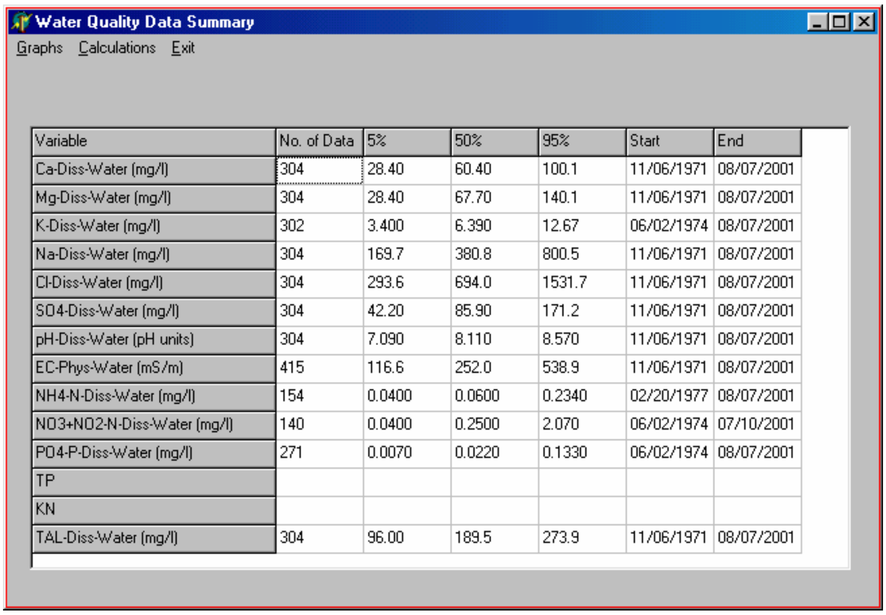


Figure 6.3 The SPATSIM data import page relevant to water quality data.

Figure 6.4 Shows an example of the data summary page of the model, where the start and end dates of the available data, the number of data points and the 5, 50 and 95 percentailes are listed for all data that are stored within SPATSIM.



Variable	No. of Data	5%	50%	95%	Start	End
Ca-Diss-Water (mg/l)	304	28.40	60.40	100.1	11/06/1971	08/07/2001
Mg-Diss-Water (mg/l)	304	28.40	67.70	140.1	11/06/1971	08/07/2001
K-Diss-Water (mg/l)	302	3.400	6.390	12.67	06/02/1974	08/07/2001
Na-Diss-Water (mg/l)	304	169.7	380.8	800.5	11/06/1971	08/07/2001
Cl-Diss-Water (mg/l)	304	293.6	694.0	1531.7	11/06/1971	08/07/2001
SO4-Diss-Water (mg/l)	304	42.20	85.90	171.2	11/06/1971	08/07/2001
pH-Diss-Water (pH units)	304	7.090	8.110	8.570	11/06/1971	08/07/2001
EC-Phys-Water (mS/m)	415	116.6	252.0	538.9	11/06/1971	08/07/2001
NH4-N-Diss-Water (mg/l)	154	0.0400	0.0600	0.2340	02/20/1977	08/07/2001
NO3+NO2-N-Diss-Water (mg/l)	140	0.0400	0.2500	2.070	06/02/1974	07/10/2001
PO4-P-Diss-Water (mg/l)	271	0.0070	0.0220	0.1330	06/02/1974	08/07/2001
TP						
KN						
TAL-Diss-Water (mg/l)	304	96.00	189.5	273.9	11/06/1971	08/07/2001

Figure 6.4 Data summary page of the water quality data analysis model.

The 'Graphs' option allows the user to show either Box and Whisker plots (Fig. 6.5) for a selected component or to enter the slightly more detailed time series analysis facility (Fig. 6.6). Figure 6.6 Illustrates that the time series analysis facility allows the user to plot 1, 3 and 5 year running means on the graphs in order to identify trends and assist in selecting the best 'stationary' period to use in later analyses. The 'Period Set' option allows the user to define the start and end dates of the data to be used in other analyses. On returning to the summary page, the summary statistics will be re-calculated on the basis of the selected data period. The final options (at this stage) perform and display (Fig. 6.7) the calculations of salt concentrations and an estimate of the present state category (still to be refined) using all the data within the period indicated on the summary page.

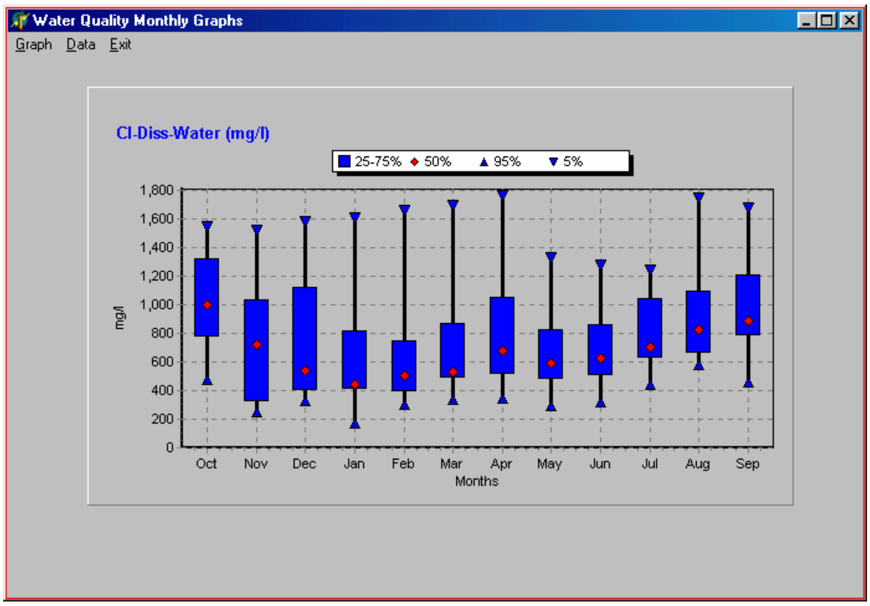


Figure 6.5 Box and Whisker plots for the chloride component.

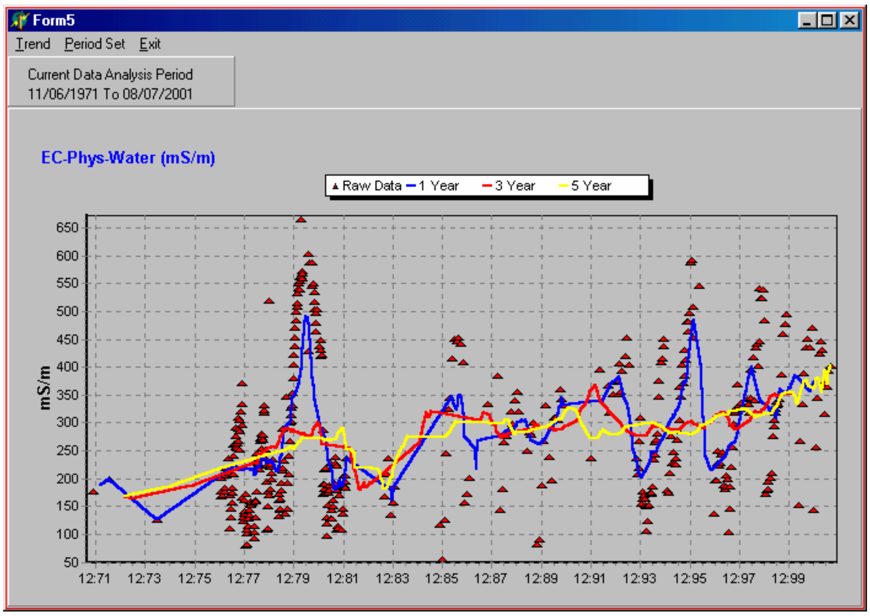
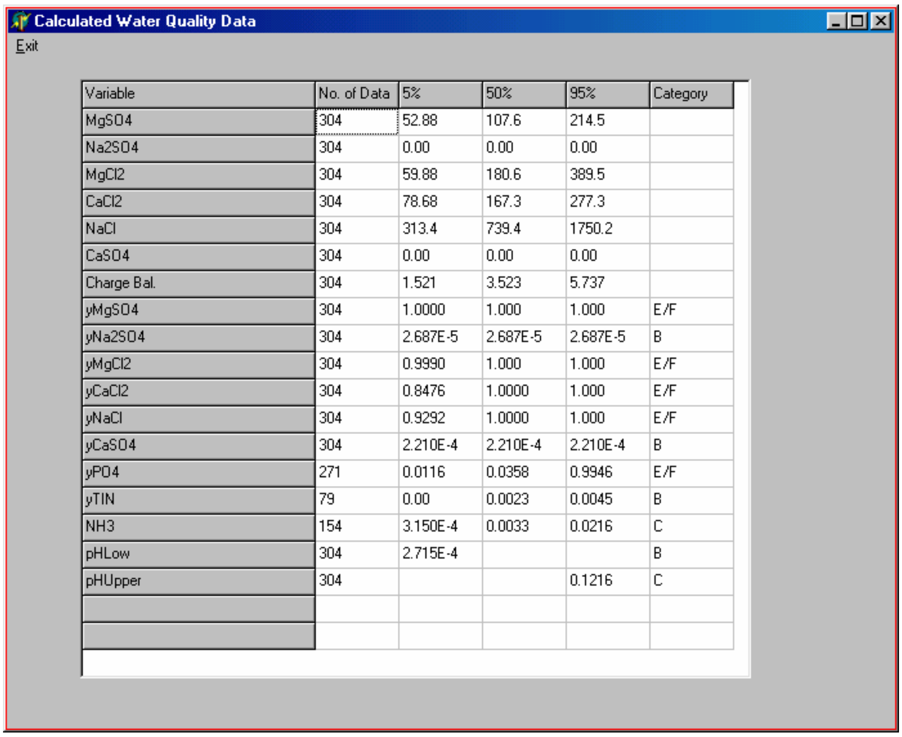


Figure 6.6 Time series analysis screen for the EC component.



Calculated Water Quality Data

Exit

Variable	No. of Data	5%	50%	95%	Category
MgSO4	304	52.88	107.6	214.5	
Na2SO4	304	0.00	0.00	0.00	
MgCl2	304	59.88	180.6	389.5	
CaCl2	304	78.68	167.3	277.3	
NaCl	304	313.4	739.4	1750.2	
CaSO4	304	0.00	0.00	0.00	
Charge Bal.	304	1.521	3.523	5.737	
yMgSO4	304	1.0000	1.000	1.000	E/F
yNa2SO4	304	2.687E-5	2.687E-5	2.687E-5	B
yMgCl2	304	0.9990	1.000	1.000	E/F
yCaCl2	304	0.8476	1.0000	1.000	E/F
yNaCl	304	0.9292	1.0000	1.000	E/F
yCaSO4	304	2.210E-4	2.210E-4	2.210E-4	B
yPO4	271	0.0116	0.0358	0.9946	E/F
yTIN	79	0.00	0.0023	0.0045	B
NH3	154	3.150E-4	0.0033	0.0216	C
pHLow	304	2.715E-4			B
pHUpper	304			0.1216	C

Figure 6.7 Display of calculated water quality variables.

6.3 THE WAY FORWARD

Although water quality methods within ecological Reserve assessments have been developed co-operatively by a team, with the guidance of the Department of Water Affairs and Forestry, the methods have not been distributed for peer review. There are also important method developments that still need to take place.

A prioritised list of actions could guide future funding and activity:

- Peer review of the methods presented in this report.
- Inclusion of turbidity, TSS monitoring and a method for TSS assessment.
- Further development of the assessment of nutrients, with more attention given to response variables such as algal growth.
- Integration of toxics and toxicity monitoring in the ecological Reserve process.

7. IMPLEMENTATION OF THE RESERVE
DA Hughes

7.1 GENERAL

This part of the report provides a relatively brief summary of the outcome of several discussions held between IWR staff and various groups within the Department of Water Affairs and Forestry (RDM Office, Hydrology and several Regional Engineers), as well as the work that was undertaken by the IWR for the WRC under contract number K8/510. Further details are available from the IWR web page (http://www.ru.ac.za/institutes/IWR, link to Hydrological Models and Software and SPATSIM), as well as the SPATSIM HELP system component 'Reserve Implementation'). All of those details are not repeated here as they are still undergoing revision and change. However, there are some basic principles and issues that are unlikely to change substantially and these are the focus of this section of the report.

Figure 7.1 illustrates some of the major issues that have already been identified and this diagram provides the 'Road Map' to the text within this section of the report. The diagram illustrates that once the Reserve has been defined there are institutional, monitoring and technical implementation issues, many of which overlap in one way or another (i.e. some institutional issues necessarily restrict the type of technical solutions that might be used for implementing the Reserve.

However, even before the implementation issues can be addressed it is necessary to consider some of the issues related to the definition of the quantity component of the Reserve and the way in which environmental instream flow assessments are converted into Reserves. The accepted (by the RDM Office of DWAF) practice for defining a Reserve is to refer to a set of assurance rules, which are essentially the flows that are expected to be equalled or exceeded for defined percentages of time. The further assumption is that the occurrence of these flows will be driven by a 'trigger' that represents the natural flow variations that would have occurred in the river under reference conditions. Reference conditions are normally taken to be natural conditions, but modified reference conditions have been used in certain situations (where for example the flow regime has been changed for a substantial length of time). The 'trigger' is designed to ensure that low flows would be required when natural low flows would have occurred (i.e. during the dry season and in droughts), while higher flows would only be required when the conditions would have been naturally wetter. This has found to be the best approach to ensuring that some of the natural variability of flow occurs within the managed flow regime and to ensure that the least amount of water is used to achieve a defined environmental objective.

The output from a Reserve determination is therefore normally a table of flows for each month of the year for a set of assurance percentages, which are considered by the ecological specialists as being likely to achieve a defined environmental objective. Typically, several such determinations are undertaken so that DWAF is provided with a range of possibilities from which the one that best achieves the overall resource quality objectives will be selected.

One of the complications is that to be able to achieve some of the components of the high flow part of the Reserve, there has to be some method of managing such flows within the catchment (it is assumed that low flows will always be able to be managed, if only by placing different levels of restriction of abstractions). In many catchments, this is not the case and there may be no methods that can be used to control high flows, or there may be limited release capacity from the available storage reservoirs. While such constraints prevail within the catchment, the Reserve that will be managed should not include those high flows and the assumption is that they will either occur and the environmental objectives will be met, or they will not occur and it is possible that the river will degrade ecologically.

Figure 7.1 Reserve implementation 'Road Map' to the major issues.

However, if at some stage in the future, the management infrastructure changes (new dams with release capabilities are constructed or extended release capabilities are constructed on existing dams), then it is reasonable to assume that those high flow components of the original Reserve will be re-instated. It is therefore critical that the details of the optimal 'design' Reserve are not lost and forgotten, despite the fact that they may not all be used in the initial definition of the 'managed' Reserve. An example could be where the only water abstractions are from small farm dams and direct run-of-river abstractions. The high flow component of the 'design' Reserve could be initially neglected on the assumption that the high flow regime of the river is unlikely to be modified to a great extent. However, if the users access to water becomes too unreliable during low flow periods, a decision may be taken to construct a reservoir to improve the yield from the catchment. In such a case, the full 'design' Reserve, including the high flow components should be considered in the design of the reservoir and if considered economically, environmentally and socially viable, high flow release capabilities should be included as part of the dam design.

7.2 TECHNICAL ISSUES

For reasons related to the issues raised at the end of the last sub-section, the technical issues have been sub-divided into those relating to large-scale systems where substantial storage exists and controlled releases are possible, as well as those where no such major storage exists. However a common area is the need to provide the regional water management authority and the on-site management team with the hydrological triggers required to convert the Reserve as defined by the RDM Office into a flow requirement at a specific moment in time.

7.2.1 Hydrological triggers

There are differences in the type of trigger that will be required depending upon the time step that will be used for checking and changing the management rules. For low flow management this time step is likely to be no less than 7 days and in many cases will be longer (10 to 30 days). However, for high flow release management the time step will reduce to at least daily and possibly even lower. For the Thukela River Reserve study, three possible methods have been identified and the generic advantages and disadvantages noted.

Gauged Records

Make use of real time information from existing or new streamflow gauges to estimate the natural flow conditions and hence the exceedence % point.

Requirements

- (1) For each IFR site that will be used for implementation and monitoring identify a gauged stream flow site that can be considered representative of the natural flow at the IFR site. This implies that observed flow duration curve characteristics are either similar to the expected natural flow duration curve characteristics at the IFR site, or that corrections (naturalisation) can be made to make them similar.
- (2) If a site is available, the stream flow record should be checked for stationarity and accuracy and the upstream impacts quantified as accurately as possible.
- (3) Establish any corrections that need to be applied to ensure that an observed flow can be translated into a natural flow duration curve % point. This will always be a problem where the observed flow duration curve has any extended flat components (such as is the case with extended periods of zero flow).
- (4) Develop the procedures for real time collection of flow data on a daily basis, through either telemetry systems or site visits.
- (5) Develop the software required to update the database of observed flows, translate any observed flow into a corrected duration curve % point and interpolate into the Reserve assurance rule table to provide the required Reserve flow at any point in time.

- (6) If an existing site is not available, locate a river site where a rated section can be established, survey the cross-section and carry out a detailed hydraulic calibration based on at least three measured flows. Components (7) to (9) must then be included.
- (7) Develop procedures and software that can be used to improve the hydraulic calibration over time based on periodic flow measurements designed to cover a wide range of flow conditions.
- (8) Establish and calibrate a hydrological model of the present day condition and simulate a reasonably long period of flows to use as a basis for establishing the present day flow duration curve characteristics. As data are collected over time, this calibration should be checked and improved.
- (9) Components (3) to (5) also need to be undertaken for a newly established site.

Advantages
- Previous records provide the flow history and duration curve shape.
- Rated sections for new sites can provide a possible cost effective method of acquiring the necessary data.
- Real time data transmission requirements would be less than for real time rainfall data and modelling.
- Dealing with streamflow data directly, rather that simulated flows.

Disadvantages
- Historical records may not be stationary nor accurate.
- Upstream impacts may be such that the gauge cannot be used to provide a reliable natural signal.
- If no suitable existing gauge can be found to represent a sub-region then it may be necessary to establish a new gauge or monitoring station. This will be potentially very expensive.

Real Time Monthly Simulation

Make use of real time rainfall (and other climatic data where necessary) in a calibrated monthly model for all required sites in the catchment.

Requirements
- (1) The first task is to identify rainfall gauging stations within the catchment that can be used as, or converted to, real time reporting stations and develop the procedures for transmitting rainfall on a daily basis to the control office.
- (2) It is inevitable that the number of reporting raingauge stations will be fewer than those used in the initial model calibration. It is therefore necessary to develop a model of spatial rainfall based on the reporting stations that can provide a similar input to the rainfall-runoff model as the set of stations used for the original model calibration.
- (3) The availability of near real time, additional hydrometeorological data (temperature, evaporation, etc.) should be identified and a procedure for incorporating such inputs into the model developed.
- (4) The original model calibrations will need to be refined to account for any differences in the hydrological forcing data (rainfall, evaporation).
- (5) The model software will need to be packaged in a way that allows for additions to be made to the rainfall and evaporation input database, the model run and the results interrogated in a user friendly manner. Some database error checking routines will also be required. Although the model operates on a monthly time step, it is proposed to update the rainfall data more frequently (once a week, or every 10 days, for

example). The model software will have to account for this and a simple rainfall 'forecasting' process for the remaining part of the month may have to be included.

- (6) The software will also have to integrate the real time estimates of natural flow with the Reserve assurance table to provide an estimate of the Reserve flow requirement.
- (7) The monthly model approach should be satisfactory for all the low flow Reserve requirements, but if high flow release information is required, additional methods will have to be developed. It is not clear at this stage what form these will take.

(8) The previous 7 tasks are all required to establish the basics of the real time management system. However, there are additional tasks that could be undertaken after implementation that could improve the accuracy of the estimates. Most of these relate to improving the estimates of the areal distribution of rainfall. Recent research results (Prof. G Pegram) suggest that the combined use of radar, satellite and ground based rainfall observations could lead to improved areal estimates of rainfall. The application of these technologies in the field of real time management of the Reserve needs to be investigated.

Advantages

- Existing model calibrations are normally available and are consistent with the flow data used to determine the Reserve and yield estimates.
- The modeling approach is more readily updateable than the system based on gauged records.
- The information can be generated for specific Reserve sites and therefore issues of transfer from one catchment to another are not relevant.
- The outputs have the potential to be used for other purposes (flood and drought warning, through rainfall forecasting).
- The need for the establishment of a reporting raingauge network provides motivation for maintaining an accurate database of rainfall information.

Disadvantages

- The available reporting rainfall stations will be fewer than were originally used in the model calibrations and therefore it will be necessary to establish a rainfall 'model' for the region.
- There is no easy way of obtaining the short period information required to provide triggers for high flow releases. This is not such a disadvantage in the Thukela system as controlled releases from the main dams are not expected to be the main provider of the Reserve high flow requirements.
- It may be difficult to obtain sufficiently representative rainfall data from a limited set of reporting raingauge stations. However, this problem has the potential to be resolved in the near future (i.e. the accuracy of the rainfall data could improve with time) using radar and remote sensing technology.

Real Time Daily Simulation

Make use of real time rainfall (and other climatic data where necessary) in a calibrated daily model for all required sites in the catchment.

Requirements

The tasks under this approach are almost identical to those for the monthly modelling approach. The details of some of the tasks may be somewhat different and more time-consuming. The points below therefore highlight these differences rather than repeating the task descriptions.

- (1) The ACRU model has already been configured for the Thukela catchment and it therefore seems logical to use this model as the starting point for the real-time management system. However, the existing results are not comparable with the flow data that are being used for planning and management of the Thukela system. It would therefore be necessary to modify the ACRU model setup to generate results that are consistent with the current inputs to the yield model and the data that were used to determine the Reserve requirements. It is also recommended that comparisons be made with gauged data so that potential problems with the existing inputs to the yield model (based on Pitman model simulations) can be flagged for future attention.

- (2) The procedures for developing the spatial rainfall model will be more complex with daily data and greater care will have to be taken to ensure that isolated extreme values measured at the reporting stations are not falsely extrapolated to ungauged parts of the basin.
- (3) The daily model offers opportunities for triggering high flow release requirements and it will be necessary to incorporate these methods into the overall software package. This should not be a problem, as a modelling strategy (the Daily IFR model included in SPATSIM) to achieve this already exists.

Advantages

- The modeling approach is more readily updateable.
- The outputs have the potential to be used for other purposes (flood and drought warning, through rainfall forecasting).
- The need for the establishment of a reporting raingauge network provides motivation for maintaining an accurate database of rainfall information.
- The daily modelling approach has the potential to provide the cues for future real time releases of high flows.
- The information can be generated for the specific Reserve sites and therefore issues of transfer from one catchment to another are not relevant.

Disadvantages

- The available reporting rainfall stations will be fewer than were originally used in the model calibrations and therefore it will be necessary to establish a rainfall 'model' for the region.
- It may be difficult to obtain sufficiently representative rainfall data from a limited set of reporting raingauge stations. However, this problem has the potential to be resolved in the near future (i.e. the accuracy of the rainfall data could improve with time). This has the potential to be a bigger problem than with the monthly modelling approach.
- The initial calibration and model set up procedures will be more time consuming and expensive than the monthly modelling approach.

Either of the modelling approaches have distinct long-term advantages, which will be applicable not only to the Thukela system, but to every other catchment in the country. The main advantages are that the approach is flexible, has value beyond the immediate objectives of implementing the Reserve, and can be established as a generic methodology for any catchment. The modelling approaches have the additional advantage of being able to make use of the results from WRC supported research projects that are expected to be completed within the next few years (for example; spatial rainfall generation methods, WR2005 and associated improvements to land use and model parameter databases, as well as improvements to the Pitman model itself).

The gauged records approach should be the one that requires the least resources to establish, although this is partly dependent on the number of new gauging sites that will be required. However, this approach does not offer any additional advantages over and above the immediate requirements of providing the Reserve triggers.

There is no doubt that the two modelling approaches require more resources to establish (and the daily model the most). However, they also offer far greater long-term benefits in terms of the integrated management of water resources in the Thukela (and other rivers) basin. There are many overlaps in the two modelling approaches and it is possible to start with the slightly simpler monthly approach and move to the more detailed daily approach at a later date when required.

Suggested real-time management plan for the low flow Reserve component.

A suggested 'model' is illustrated in Fig. 7.2 and is considered to be applicable for those situations where the main management control is the implementation of restrictions on licensed users rates of abstraction. It is also based on the perception that it is not practical to manage the Reserve at the same level of resolution with which it was defined.

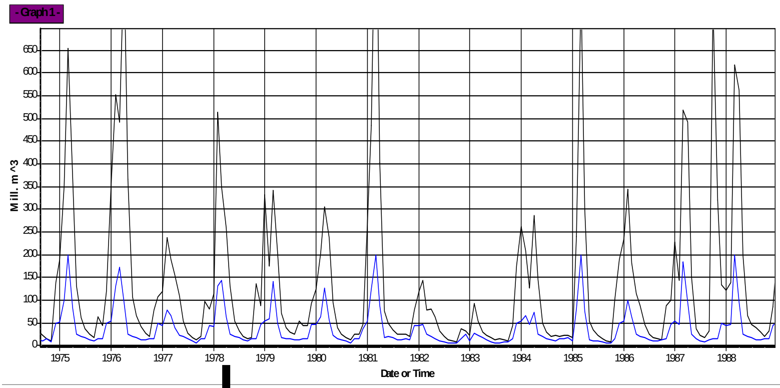
Principles:

- Real-time rainfall inputs are all that the management agency are required to collect.
- The rainfall-runoff model and data processing (i.e. duration curve and assurance rule interpretation) routines would be packaged in a user-friendly way that would appear as a 'black-box' to the standard user, but would be accessible for re-calibration when and where necessary.
- The rainfall-runoff model calibration would be based on the same approach as that considered acceptable to the water resource manager (i.e. WR90 or WR20005 by default or any data that were used in an existing yield model).
- Abstraction licenses would need to be expressed in terms of the flow condition category. Any basis for curtailment of supply would be expressed in the same terms (e.g. Conditions II to V: full allocation. Condition II: small curtailment. Condition I; no allocation. **OR** Conditions II to V; full allocation. Condition I; curtailment to 20%).
- The % point boundaries for the category divisions could be fixed on the basis of the Reserve data in combination with the type of abstractions and could be agreed with a range of stakeholders.
- The rainfall input and modelled flow condition would be updated on a 7 to 10 day cycle. The exact cycle length could depend upon the system of real-time rainfall data collection and the number of reporting stations involved.
- The real-time flow condition would be made available to all water users via a web page, dial-up message system or similar approach.
- Routine operation of the system would involve:
  - Collecting the real-time rainfall data.
  - Entering these data into the system.
  - Clicking an 'UPDATE CONDITION' button.
  - Reading the output of the condition and Reserve requirements.
  - Posting the condition to the public information source.
- Actions to ensure that the Reserve will be met will very much depend upon the specific situation but may involve the adjustment of releases from a reservoir. The assumption is that abstractions will fall within the range of licensed abstractions, but will never be constant and therefore there will be substantial variability in the flows within the river.

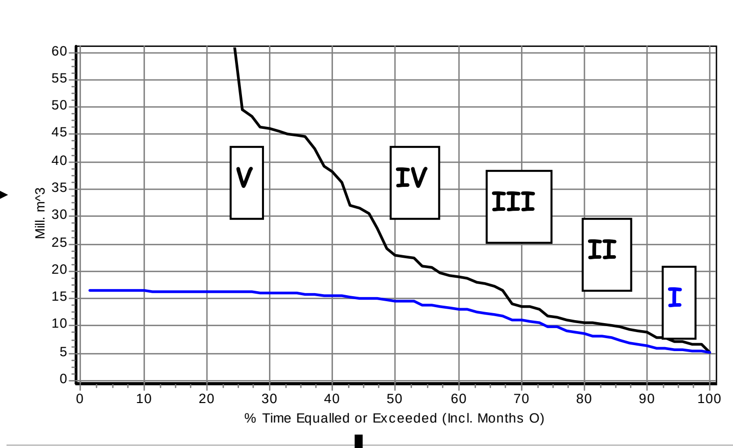
Real-time rainfall data (7-10 day cycles) from reporting stations, collected by water resource management agency.

Data input and processing routines

Pre-calibrated rainfall-runoff model based on WR90 or WR2005, using rainfall data from the reporting stations.



‘Black-Box’ processing routines perform internal comparison of real-time generated natural flows with duration curves and Reserve assurance rules.



Output to the manager is a ‘Flow Condition’ category and a range of Reserve flows within which to manage. Users licenses can be expressed in terms of the category (e.g. 500 Ml/month while > III, 250 Ml/month while > I, no abstractions if at category I). The category can then be ‘broadcast’ to water users in real time and any Reserve releases can be based on the category. For example:

Category	Condition	Reserve Requirement (Oct – $m^3 s^{-1}$)
V	Wet	5.4 to 6.2
IV	Less than average	4.3 to 5.4
III	Moderately dry	3.2 to 4.3
II	Dry	2.4 to 3.2
I	Drought	1.9 to 2.4

Figure 7.2 Suggested ‘model’ for real-time implementation of Reserve low flows.

Hydrological triggers for high flow releases

The Daily IFR model has been established for the purpose of defining time series of Reserve flow requirements, as well as to estimate the requirements in real time on a time scale of 1 day. While the model estimates both low and high flow requirements, the low flow component can be ignored (and the alternative offered in the previous sub-section used in its place) and the model used for high flow releases only. The basis for the high flow release component is to estimate the probability that a forthcoming event in a natural daily time series is likely to be a suitable triggering event for a high flow release. Inevitably, some form of 'prediction' is required to ensure that releases occur more or less simultaneously with the trigger event. To avoid the need for a forecast, the rate-of-rise of the river on the current day is used to determine the probability that a suitable trigger event will follow. The calculation of that probability is based on a prior analysis of all events in the natural time series (i.e. the model requires a 'reasonable' length of historical data with which to calibrate the relationship between rate-of-rise and event size).

The model has been demonstrated to generate acceptable results when used as a Reserve requirement design tool with a long time series of natural daily flows. In the case of the Daily IFR model, the trigger flows do not have to be related to the Reserve site, they simply have to reflect the same flow variability characteristics as the site (which can be translated into the requirement that the same climate and meteorological driving forces and similar catchment reponse forces apply to the trigger and Reserve sites). However, if it is to be used in real time the trigger data will be required with a very short delay (less than 1 day), otherwise the trigger event will have past before the release decision can be made. There are a number of other issues related to attenuation, losses and tributary inflows that need to be considered before an optimal management system can be designed and implemented. These are covered in the next section.

7.2.2 Large-scale systems with storage

These are situations where one or more major dams exist (or will be constructed) in the system and where these can be used to control downstream flows to a greater or lesser extent. There is therefore scope for managing flows and using storage management to satisfy both the Reserve and the water users. However, it is critical that a system yield has been determined that is compatible and achievable with the design Reserve in place. It is also critical that the system is managed in a similar way to the operating rules that were used in the assessment of the system yield during the design phase. Although the management control in this type of situation is greater, the resources required to manage the system to achieve the Reserve with a mimimum impact on other users (i.e. optimally) could be far greater than in the simpler situation referred to below in section 7.2.3.

There are situations where there are no high flow release capabilities or requirements, in which case the management approach becomes simpler and monthly flow trigger data would be sufficient. The main additional consideration in determining the releases required to satisfy a downstream Reserve would be to account for transmission losses (through channel seepage and evaporation, as well as abstractions) and gains (through tributary inflows or artificial return flows).

Where there are high flow release capabilities, the management system and the real-time data requirements become more complex.

Accounting for tributary inflow events

If the Reserve site (i.e. the river cross-section or reach where the Reserve was determined) is a long distance from the reservoir release site, it is possible that tributary inflows could contribute to satisfying the Reserve if inflow events occur more-or-less simultaneously with events in the main channel. If this is the case, the releases from the reservoir can be substantially reduced. 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 streamflow 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.*

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 Fig. 7.3 for an example of the results display). 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.

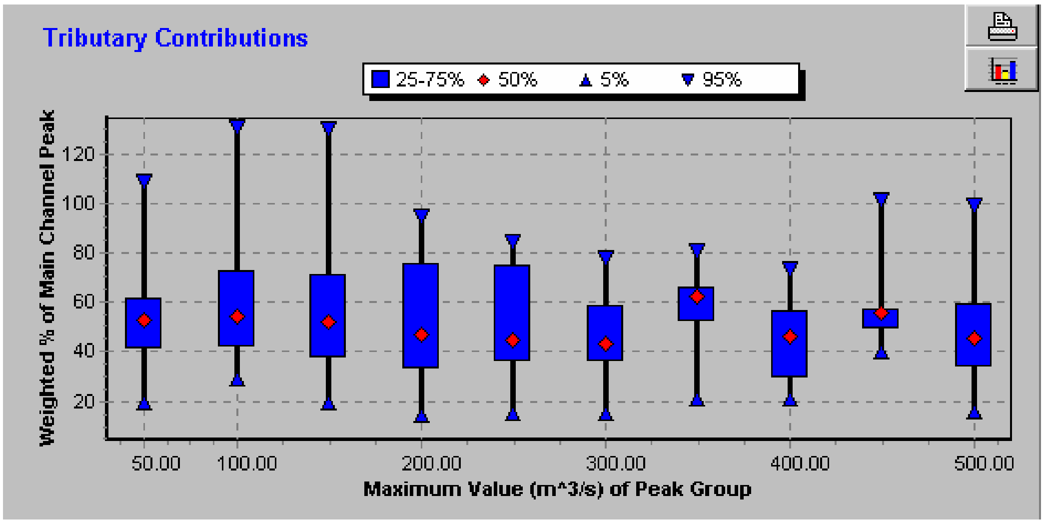


Figure 7.3 Results output from the Tributary Inflow Analysis model

Attenuation of released flows

This issue is strongly related to the tributary nflow issue and concerns the attenuation of a release hydrograph as it moves along the main channel between the reservoir and Reserve site. The implication is that a higher peak flow (or a longer peak release) will have to be released than is required at the downstream Reserve site (while also accounting for potential tributary contributions). It is clearly important to determine what the optimum level of release should be so that the downstream requirements can be met without releasing excessive quantities of stored water. This is unlikely to be an easy issue to resolve, as most hydraulic routing models require extensive channel x-section information along the whole reach through which the released flow will pass. In most situations these data will not be available and will be either difficult or expensive to collect. The Institute for Water Research is investigating the problem and attempting to develop a model that can be used to calibrate the parameters of the simple Muskingham storage routing equation. If relationships can be determined between channel parameters (length, slope, type, etc.) that are readily obtainable and the parameters of the routing equation, then a practical method of assessing the degree of attenuation can be developed. Another alternative is to undertake test releases and monitor the degree of attenuation across a range of peak releases.

Identifying Reserve floods to be managed

Within a Reserve definition there may be large floods specified which are designed to ensure that the channel physical dimensions and large sediment dynamics do not change over time. If these floods are not present in the future flow regime there is the potential that the size and shape of the channel will change and therefore that the relationships between flow and habitat for the other ecological components will also change (therefore negating the purpose of managing the flows for the Reserve). However, in many cases it will not be practical or possible to provide these flows as managed releases. The normal assumption is that such flows will continue to occur through uncontrolled spillages from the reservoir. This can be assessed to a certain extent during the scenario analysis phase of the system design. The system yield model can be used to check that the reservoir does spill at times when large floods occur in the naturalised time series and that the volume of spill is sufficient to assume that the peak flow would be enough to satisfy the Reserve requirements.

Problems are only likely to be experienced in cases where the reservoir is very large in comparison with the volume of large flood hydrographs and if the level of storage is likely to be quite low at times when floods are expected to occur. This may be the case in multiple reservoir systems where one or more reservoirs are constantly drawn down, while others are used for the main system storage. There is no simple generic answer to this issue and each situation should be evaluated individually.

7.2.3 Small-scale systems

The technical aspects of Reserve implementation should be simpler under these conditions and given the lack of control over high flows, should focus on low flow management largely through licensing. It is important to recognise that the resolution and accuracy with which a Reserve is determined in small catchments will frequently be much lower than for major rivers. This is related to the fact that it is usually not cost effective to undertake detailed Reserve determinations on all small rivers and therefore more rapid approaches, based on regional extrapolation, are frequently used. In addition, Reserve determinations on major rivers normally incorporate some assessments of the Reserve against present day and future planned water use, as well as a component of stakeholder input into the determination process. This allows various Reserve scenarios to be assessed and modified in an iterative process that frequently results in a compromise solution that is ecologically sustainable and satisfies the water demands of users. This process is absent when Reserve determinations are undertaken for smaller scale water bodies and it seems to be the assumption that the Regional Offices of DWAF (and eventually the CMAs) will have to provide the equivalent process when interpreting the Reserve and putting it into practice. However, it is apparent that guidelines on how to achieve this have not been developed yet.

The assumption has been made that the highest priority related to implementing the Reserve in situations where no large reservoirs are present is the need for assessing new abstraction or SFRA license applications and determining whether these can be permitted without the Reserve being violated. The critical issues are therefore to be able to define the natural flow regime, the present day flow regime (or an estimate of the present day water usage), the Reserve and the estimated effects of any new license applications. These can then be compared to provide a basis for decision making. It is suggested that the most appropriate way to compare the different flow regimes (natural, present day and future) is to make use of flow duration curves as these are compatible with the assurance rule table method used to define the Reserve requirements by the RDM Office of DWAF.

The sub-section on '*Suggested real-time management plan for the low flow Reserve component'* is appropriate for managing systems of this type and the following sub-sections focus on the water use licensing issues.

Information Requirements

To be able to assess license applications adequately it will be necessary to evaluate the existing water use, as well as future required water uses (i.e. license applications) and their impact on the natural flow regime so that these impacts can then be compared with the requirements that have been established for the Reserve (see the next section on 'Assessing level of use against the Reserve'). It should be noted that the Reserve is defined as a set of flows for different levels of assurance. This means that water use (both present and future) should be assessed in the same way if the information on water use and the Reserve are to be compatible and comparable. In simpler terms this implies that it will be necessary to understand the impacts of various current and future users on the natural flow regime under different conditions (i.e. during normal flow periods, as well as during wetter periods and during droughts) and seasons of the year.

One of the critical issues that has been identified with respect to some small scale systems is the lack of readily available information on the natural flow characteristics of sub-quaternary catchments. The WR90 database (Midgley et al., 1994) default information on natural flows has proved to be inadequate in catchments where there are substantial spatial variations in rainfall and runoff characteristics (such as in areas of steep topography and rainfall gradients). Simple scaling has often been demonstrated to under-estimate the low flow component of sub-quaternary headwater rivers. Hughes (2004b) investigated this problem using all sub-quaternary scale gauged catchments within South Africa. A modified scaling approach based on the ratio of sub-quaternary to quaternary mean annual rainfall appears to offer some advantages over simple catchment area based scaling methods. However, the limited amount of observed data available for such an analysis makes it difficult to assess the applicability of the approach to catchments throughout South Africa. A facility for calculating the scaling factor and the associated rainfall database has been incorporated into SPATSIM (see Section 2.3.5 'Sub-Quat. MAR Option').

For the type of situation being considered, the types of water use are limited to streamflow reduction activities (mainly afforestation), small farm dams and direct run-of-river abstractions. Storage should not therefore play a major role in determining patterns of water use. It is already known that afforestation impacts to a greater relative extent on low flows than it does on high flows. The CSIR have approximately quantified these effects for two different tree types and growth conditions, while more recent research by the CSIR and the Universities of Natal and Stellenbosch has quantified these effects in more detail.

The only way to limit run-of-river abstractions during drought periods is to license the normal required abstraction level with a limited level of assurance and to prohibit (or reduce) abstractions during drier periods. While this principle can be applied to new license applications, information of this type may not be readily available for existing users (the issue of ensuring that users comply with such license conditions is a different matter). The only way to ensure that contributions to low flows continue from catchments above farm dams is to ensure that a requirement for low flow releases form a condition of the license granted before construction of the dam can take place. Again, it is possible to consider these effects for new licenses, but whether low flow releases are being made from existing dams may not be information that is available.

All of the above issues create complications in defining the effects of present day and future water use. However, it should be possible to provide the required information, if only with a relatively low level of detail or confidence. It has been suggested that the WSAM system could provide information of this type at a relatively course scale.

Assessing Use Against the Reserve

The Institute for Water Research has developed a simple model that allows existing water use, as well as potential future water use, to be used to estimate present and future flow regime conditions and compare the result with the flows that are required for the Reserve. The information required to run this model is as follows:

- A monthly time series of natural flows (obtainable from WR90 or updated simulations).
- A table of assurance rules for the Reserve that forms the standard output from the RDM Office as part of the Reserve definition. Two tables can be used, one that includes the high flow component of the Reserve or one that excludes the high flows.
- EITHER: A monthly time series of present day flows that may have been generated as part of the Reserve study to assess present day conditions. OR: Information on the present day levels of afforestation (tree type, rotation period and growth conditions), the storage volume, catchment area and annual abstraction from small farms dams, the annual abstraction volumes at several assurance levels from run-of-river schemes and the seasonal distributions of the small farm dam and run-of-river abstractions (see the screen image in Fig. 7.4 for more details).
- The equivalent information on afforestation, small farm dams and run-of-river abstractions to the above for new license applications.

The model uses the above information to generate flow duration curves for natural, present day and future conditions and allows graphical comparison of these with the Reserve requirements (which are effectively expressed in the form of flow duration curves). The results are displayed in two formats (Fig. 7.5): The first is the flow duration curves for the selected calendar month across the full range of perecentage points. The second is a view of all the months for one selected duration curve percentage point.

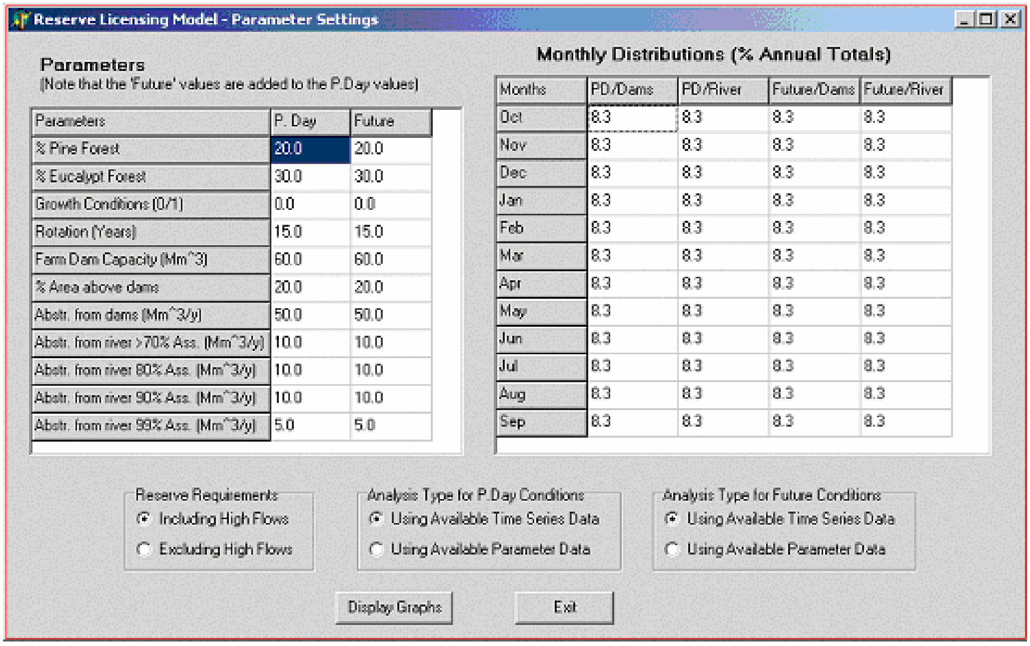


Figure 7.4 Input data screen for the Reserve Licensing model

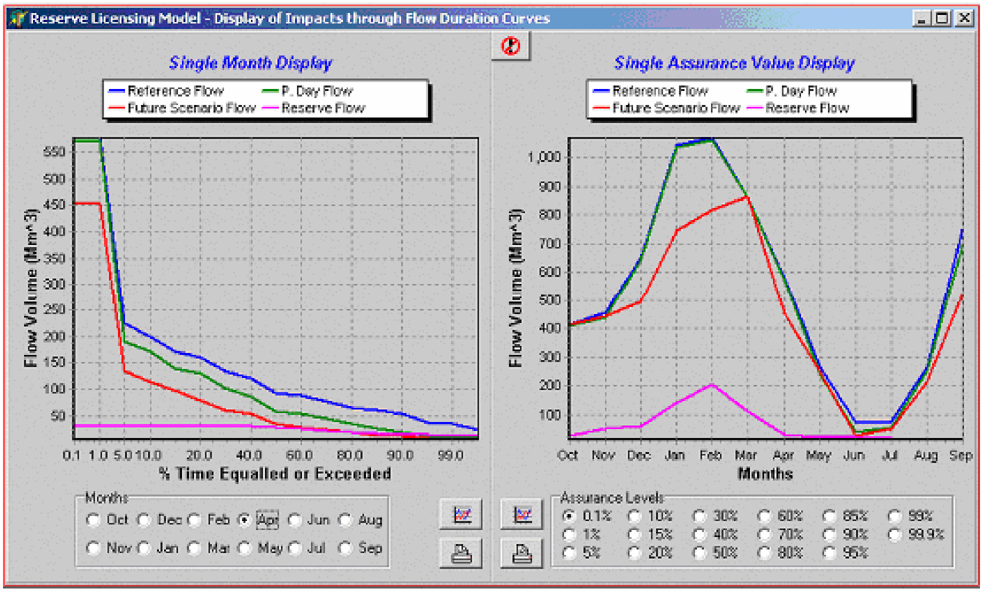


Figure 7.5 Graphical results for assessing the Reserve against natural, present day and future (scenario based on license applications) conditions.

In very general terms, if the Reserve assurance curve lies above any of the other curves then it can be concluded that the Reserve will not be satisfied. The sub-section on *Decision Making* discusses this problem and several issues about what to do in such circumstances in more detail.

Information availability

The first two requirements will always be available with at least reasonable accuracy. WR90 data can be used for the time series of natural flows, although these data need to be treated with caution when dealing with sub-quaternary scale catchments (see Hughes, 2004b). The Reserve requirements will normally be supplied from the DWAF RDM Office in the correct format. However, the Desktop Reserve model can also be used to generate the correct information. This is a very simple model to use if all the default parameter settings are accepted.

The requirement of either a time series of present day flows, or the details of present day water use may be a more difficult information requirement to satisfy. It has been noted by some regional offices of DWAF that accurate information of this type is not always readily available. One of the problems is that during the process of registering existing use, many users are attempting to register what they would like to use rather than what they are using. During the SANCIAHS symposium (Port Elizabeth, 2003) it was suggested that a hydro census based on land use (from air photos or satellite imagery, for example) could be useful in this regard. However, it was also pointed out that it is often difficult to translate agricultural land use into water use due to the different volumes of water used per hectare by different irrigation methods. Ultimately, what is required to make this particular SPATSIM 'model' useful are regional databases of individual water uses which can then be integrated at any catchment scale required. It is inevitable that additional facilities would also be required within SPATSIM to enable the information for a number of water uses to be quantitatively integrated to the required catchment scale, but this is not a major task.

The final requirement should be relatively straightforward as the amount of water and the level of assurance is assumed to be part of the license application.

Interpretation and Decision Making

There are a number of issues related to interpreting the results of the simple model, some of which are related to the Reserve and some that will be related to the definition of licenses and the ability of the licensing authority (Regional DWAF Offices or CMAs) to issue licenses that include conditions.

One of the Reserve issues that still requires attention is the perception that drought low-flow requirements have been set that are identical to the natural drought low flows. Clearly, if this is to be accepted as a limitation on resource development, then NO afforestation would be permitted (either present day or future), unless low flows downstream of the afforestation can be artificially augmented. Similarly, no abstractions would be allowed with 100% assurance of supply as these would reduce the future drought low flows. This issue needs to be resolved with the Reserve specialists and the drought flow Reserve requirements given more attention. Figure 7.6 illustrates the problem by showing spatial distribution of drought Reserve requirements for the lowest 4 months of the year (estimated using the default parameters of the Desktop Reserve model) relative to the natural flow for the same period. The 10% category includes those situations where both the drought requirements and the natural flows are zero. Figure 7.7 provides a cumulative frequency distribution of the values, which demonstrates that about 85% of the quaternary catchments require less than 50% of the natural flow during droughts (based on the Desktop model estimates).

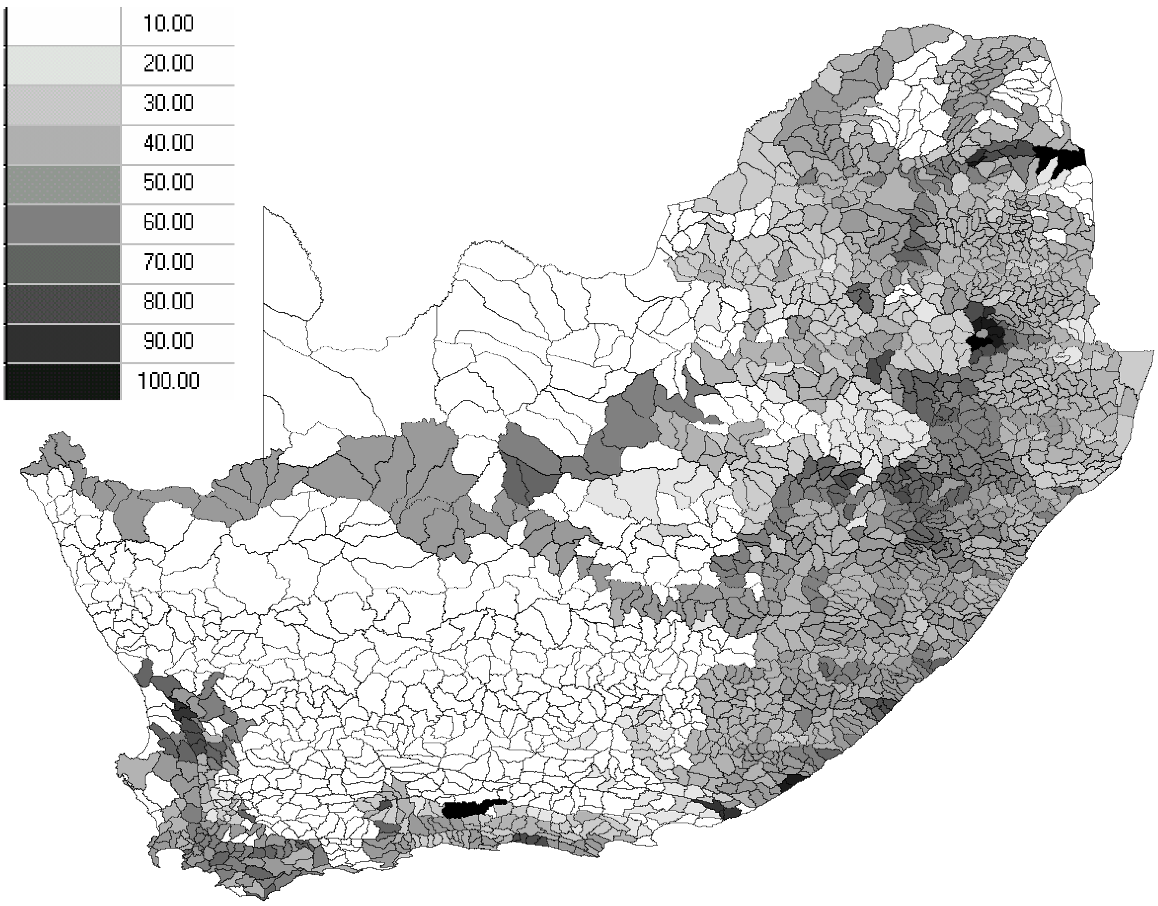


Figure 7.6 Spatial distribution of drought ecological Reserve requirements for the lowest 4 months of the year as a % of the natural flow for the same period.

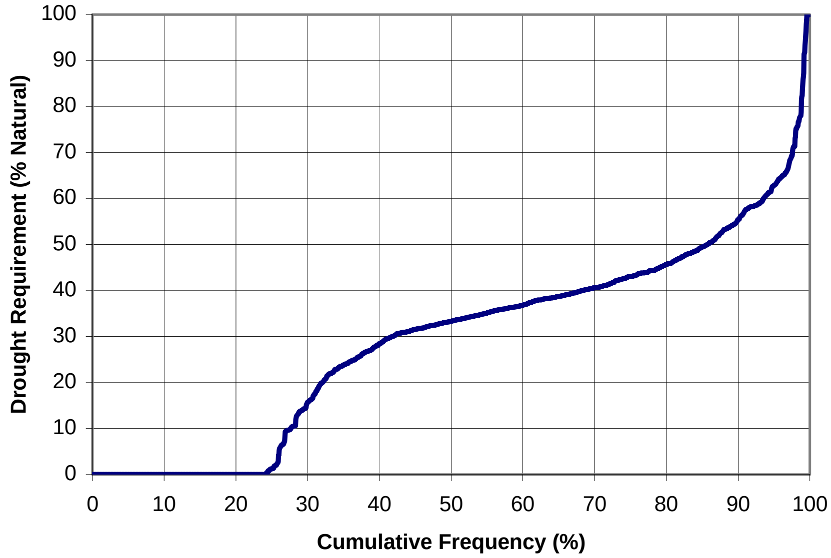


Figure 7.7 Cumulative frequency distribution of drought ecological Reserve requirements as a % of the natural flow for the same period.

The situation is apparently not as bad as it is perceived, although there are clearly some parts of the country where the issue is serious.

There will be situations where the present day situation lies close to the Reserve and it will be clear that any further licences that are accepted will violate the Reserve. However, there will also be other situations where the Reserve is only not being met for certain months and limited amounts of time on the flow duration curves. It is necessary to understand that all Reserve definitions (even those determined using comprehensive methods) have limitations with respect to the resolution of the data. If the present day or future flow duration curves cross the Reserve assurance curves only by a relatively small degree, it is reasonably possible that the objectives (in terms of environmental sustainability) are still likely to be met. It is not possible (at this stage) to offer straightforward guidelines about how to assess situations where the Reserve requirements are not being met to a significant degree. The answer will be highly site specific and could be related to a number of issues including:

- The known sensitivity of the environment to flow reductions.
- The extent to which flows, rather than non-flow related issues are impacting on the river and determining the management category.
- The position on the duration curves where the problem lies.

Given the existing status of knowledge and understanding, the most appropriate approach would seem to be to consult local ecological Reserve specialists and obtain comment on the likely impacts of not meeting the Reserve to the degree illustrated by the flow duration curve graphs generated by the simple model (Fig. 7.5). It is the intention of the IWR to add some decision support components into the simple model that will NOT provide an answer but WILL suggest generic alternatives and approaches to follow under different circumstances. It is likely that these will only be determined as more experience of implementation and licensing is gained. Feedback to the IWR from the Regional Offices of DWAF is therefore essential.

7.3 MONITORING AND COMPLIANCE

This section refers to the monitoring of the ecological condition at a Reserve site and the long- term assessment of the extent to which there is compliance with the ecological objectives of the Reserve (which includes checking that the Reserve flow requirements are being provided). None of the WRC projects associated with this report were designed to explicity address these issues. However, the following briefly summarises some of the approaches that were discussed at the workshop that was convened to design monitoring protocols and a DSS for the Thukela River (IWR Source-to-Sea, 2004)

The following assumptions are made prior to the Reserve monitoring DSS being implemented:

- Both the Present ecological state (PES) and Ecological Category (EC) derived from the Management Class have been specified in qualitative and quantitative terms. This is a product of the Ecological Reserve determination process.
- Water quantity and quality specifications for the ERC are available.
- A particular Decision Support System has been followed to determine whether Compliance Reserve Monitoring is required.

The first part of the monitoring process is to establish baseline requirements. These are required so that the basis for identifying Thresholds of Probable Concern (TPCs) can be identified during the long-term monitoring process. There are several critical questions that have to be answered

- Where does the Reserve need to be implemented (it may not be at all sites used in a determination)?
- Do low flows, high flows, or both need to be implemented?
- How can the Reserve flows be implemented (what are the controls and release mechanisms involved)?
- Is there sufficient information available from the Reserve study to serve as a baseline?
    - For Compliance Reserve monitoring.
    - For Ecostatus Reserve monitoring.
    - If no, what is required to collate sufficient information?
- For Ecostatus monitoring, what actions, how frequent and by whom are required?
- For Compliance monitoring, what actions, how frequent and by whom are required?
- When the monitoring is underway, what happens when a TPC is exceeded?
- If a TPC is exceeded, is this due to flow or non-flow related problems?
    - If flow, are the Reserve flow requirements being met?
    - If they are then a re-evaluation of the Reserve determination is required?
- A similar set of questions could be asked for water quality.

From a hydrological point of view it is necessary to establish the basis for determining if the Reserve flows are being met (i.e. what information or method will be used to cue the Reserve requirements).

Baseline monitoring decision support system (BMDSS): concepts (for further information contact: CJ Kleynhans, DWAF)

In terms of drivers, the following are the relevant objectives of the monitoring process:

- Hydrology: To interpret changes in biological response components and to identify whether flow is a cause/problem.
- Water Quality: To interpret changes in biological response components and to identify whether the problems are point and/or diffuse source, or flow related.

- Geomorphology: To interpret changes in biological response components and identify whether it is flow or non-flow related.
- Habitat: To aid in interpreting changes in biological response components. To use as a TPC and substitute for detail biological information if necessary.
- Riparian Zone (as a Driver): If considered as a driver - to interpret changes in biological response components and identify whether it is flow or non-flow related.

In Terms Of Biological Responses, The Following Are Relevant Considerations For Their Inclusion In the BMDSS:

- Fish, Invertebrates & Riparian Vegetation: Specification and assessment of whether Ecological Reserve Category and Ecological Specifications are being attained.

Further details are available within the HELP files of SPATSIM.

7.4 INSTITUTIONAL ISSUES

It is reasonably clear that DWAF does not possess the resources to 'police' the compliance of users with the terms of their abstraction licences. It is unlikely that the future CMAs (Catchment Management Authorities) will have the resources or capacity to do this either. It is therefore vital that the broad community of water users in the country buy-in to the concepts of the South African Water Law and especially the concept of sustainability and the Reserve. The Water Research Commission publication by Palmer et al. (2002) provides a clear and simple explanation of the concepts and the background to this aspect of the Water Law that should be understandable to a large proportion of the community.

Water User Associations and the concepts of self-management have a very important role to play in ensuring compliance and without the cooperation of such groups, it is unlikely that the Reserve components of the Water Act will ever be implemented in a sustainable way.

There are a number of other issues associated with the capacity and training of staff in regional (or basin) water resource management agencies that relate to their ability to interpret and collate available information and to run analysis methods or models. Every attempt should be made to ensure that models or information storage and analysis systems are designed with the typical technical skill level of such staff taken into account. However, there will always be a need for some training in the application of such systems and these training requirements need to be identified and programmes put in place as a matter of urgency. Should this not take place, it is unlikely that these agencies will be able to acquire the capacity to implement the Reserve even in the simplest of situations.

There will also be situations where it is not cost effective to employ staff within the regional agencies to perform some specialist tasks that are required to support the establishment of Reserve implementation programmes. In such cases it will be necessary to employ consultant Reserve specialists and it is important that such organisations and individuals are available. This implies that additional training is required so that the required specialist skills do not only rest with a small and dwindling (over time) number of individuals.

A final point that has been raised by several regional water resource management staff is the need for the Reserve to be viewed within the whole range of water resource management options. Specifically, reference has been made to the need to implement demand management and loss control. It is unrealistic to expect an 'environmental conservation and sustainability' component (i.e. the ecological Reserve) of water management practice to be effective, without implementing adequate parallel components to ensure efficient and beneficial use of the resource. The authors of this report are not qualified to propose demand management procedures and it was certainly not part of the project. However, the quantities of water ‘wasted’ in various water use sectors are reasonably well known and documented and it is not difficult to make comparisons between these quantities and those typically required for Reserve purposes.

8. DEPLOYMENT OF SPATSIM AND FUTURE DEVELOPMENTS
DA Hughes and D Forsyth

The recommendations of the study on the commercialisation of models and software developed with Water Research Commission funding are given in Hughes at al. (2004). From this study it is reasonably clear that the most appropriate approach to ensuring the sustainability of a software package, such as SPATSIM, is to develop a broad base of users through training and ongoing support. The study also found that it is important that the software is supported by adequate help information.

At the end of 2003 several SPATSIM training courses had already been held and the IWR had licensed some 22 users. While it is recognised that there are still some parts of the software that require modification to improve the functionality and user friendliness, the developers at the IWR are confident that the product is market ready. There are sufficient help facilities already in place for first time users to progress after an initial training session of 1 to 3 days in the concepts and basic functions.

The IWR is obliged to charge a nominal fee of R1200 (at 2004 prices) for the deployment license of SPATSIM as this is related to the use of ESRI Map Objects (who charge an application development fee). A typical 2 ½ day course with between 6 and 12 participants will cost R3000 to R4000 (including the presenters travel, subsistence and professional fees, as well as the license fee) per person. The courses are designed to cover the following and the example applications will be tailored to meet the requirements of the participants:

- Basic design concepts of SPATSIM
- SPATSIM Help facilities
- Setting up SPATSIM applications
- Importing data into SPATSIM
- The time series display and analysis utility (TSOFT)
- Setting up model applications
- Example applications
- Future developments and updates

The basic course is designed to ensure that participants have sufficient background to start making use of the software, but will not cover the details of individual models associated with SPATSIM. Many of these are relatively easy to use and do not require specialist training, while others are more complex and do require further training to use them effectively (such as the daily VTI model, the water quality Reserve methods and the Rapid Simulation model). Courses on the use of SPATSIM for specific applications can be arranged on demand and the costs will be very dependent on the number of participants and the level of training required. In some cases course presenters who are not part of the IWR may be required (this applies to situations where third party organisations have incorporated their models into SPATSIM (e.g. Rapid Simulation model).

The basic components of SPATSIM are not likely to change substantially in the future, although small modifications to remove 'bugs' and to improve functionality will continue to be made as they are identified. The help files have also reached a level of maturity that suggests that most of them will not change that much. However, additional 'Road Map' type help files are expected to be added as the need for them arises and as time allows. The major changes are therefore likely to be in the addition of new and improved external applications. The IWR has put in place a web based update system such that all changes are posted on the IWR web site (http://www.ru.ac.za/institutes/iwr and look for the Hydrological Modelling and Software link and then the SPATSIM Update link) as downloadable, automatic installation update files. These updates are fully documented (in terms of date and nature of updates) on the web site. At the same time the current help system is also available on the web site as html files.

The IWR has received several enquiries about adding models or data analysis methods to SPATSIM. All of these will be costed and managed on an individual basis. In some cases the changes may be quite minor, in which case the IWR will be able to make the modifications at no extra cost. In other cases the organisation requesting the change will be provided with a cost estimate for the new development. Where such developments lead to a change to the main part of SPATSIM, all users will benefit without cost or restriction. However, where the developments involve the addition of a new external application (a new model for example) it will be up to the organisation paying for that development to decide whether it becomes part of the standard SPATSIM package or whether its distribution is restricted in some way.

The source code of SPATSIM will remain the property of the IWR as no single funding agency has contributed to the development to the same extent as the Institute. However, in recognition of the major contribution of the Water Research Commission a copy of the source code will be lodged with the WRC and the copyright will be shared between the WRC and the IWR. Additional contributors will be acknowledged but will not share in the copyright. At the same time it is unlikely that any other organisation will be able to make modifications as effectively as the Institute and it is never a good idea to have more than one version of the source code in existence at the same time. However, the details of the database structure and the basic design of the system are well explained within the help files. If there are sound reasons for passing on the source code to a different organisation to ensure the future of the software, or to enhance its further development, it is unlikely that the IWR would have any objections.

The IWR is conscious that the software can be relatively complex to apply for a new user and is continuously looking for new ways to improve the help system. An FAQ (frequently asked questions) list has been established on the IWR web page and the possibility of a keyword index is being investigated, as is the development of worked examples for some of the more common applications.

In general terms, the IWR is committed to the future support of SPATSIM in the short to medium term. It is well known that computer technology changes rapidly these days and it is inevitable that in the longer term SPATSIM is likely to become obsolete in its current form. Whether it will be worth upgrading the system to account for major changes in technology is a decision that will have to be taken at the appropriate time, but will certainly require a quite substantial funding commitment.

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APPENDIX A:

METHODS TO ASSESS INDIVIDUAL WATER QUALITY VARIABLES AND PRESENTATION OPTIONS

TABLE OF CONTENTS

1. METHODS TO ASSESS INDIVIDUAL WATER QUALITY VARIABLES

1.1 INTRODUCTION

These methods are based on methods first described in "Methods for assessing water quality in ecological Reserve determinations for rivers, Version 2, Draft 15.0" (DWAF, March 2002). The methods were assessed at a workshop held in Grahamstown in July 2003, and refined. The revised methods were posted on a webpage for further comment and have been incorporated into SPATSIM.

The methods as currently posted on the webpage have been included as part of this report, as this is the current status of methodology available to undertake ecological water requirements (Rivers) assessments for water quality (March 2004). This version has also been included in SPATSIM and any subsequent changes in the methodology will necessitate changes in SPATSIM.

The methods are now considered suitable for peer review (Rossouw, ed., 2003).

Refinement of methodology to include use of conductivity and Total Dissolved Salts, commonly used parameters to rapidly assessment prevailing water quality conditions, has since been undertaken. These methods have not been included in SPATSIM, but may be included in future versions.

There are gaps in the methodologies currently available in SPATSIM:

- The method for calculating the salts from relevant ionic data has not been able to be included in SPATSIM and therefore the March 2004 version of SPATSIM will not be able to perform this functionality.
- Not all methods have been fully developed.
- Not all water quality variables are provided with a method to adjust the default boundary table.
- Not all default boundary tables have been populated.

Web sites and Spatsim Notes:
The relevant documentation are currently housed on one of the project team's webpages (Rossouw, Ninham Shand; see web address listed below). However, it would be more appropriate that the relevant documentation (final versions and documentation that specialists are required to use in EWR assessments) are housed on a webpage maintained by relevant organisations, such as the Department of Water Affairs and Forestry (in particular, the RDM office) to ensure that updates to water quality methods are disseminated rapidly for incorporation in EWR assessments. The documentation presented in this appendix is also included in the "Help" section of SPATSIM and as methods are updated, it will become necessary to update the SPATSIM version.

http://projects.shands.co.za/hydro/hydro/WQReserve/main.htm

1.2 INORGANIC SALTS

1.2.1 Rationale

Inorganic salts: Sodium chloride, sodium sulphate, magnesium chloride, magnesium sulphate, calcium chloride, calcium sulphate.

Why use salts rather than ions?

There is no doubt that in some cases sufficient data exist to ascribe the toxicity of a salt to either a cation (such as Cd^{2+}) or an anion (such as CN^-). However, in the case of common salts such as Na_2SO_4, $MgCl_2$, $MgSO_4$, NaCl etc., it is considerably more difficult to ascribe the effect to either the cationic or anionic component of the salt. There are indications that some of the alkaline cations (such as Na^+ and K^+) and alkaline earth cations (such as Ca^{2+} and Mg^{2+}) are physiologically important, either by innately or as ratios. However, insufficient data appear to exist to derive EcoSpecs for ions in isolation. Consequently the approach used is based on the measured toxicity of salts.

The approach for setting the Reserve for major inorganic salts is based on a hazard assessment. More information on hazard assessment appears in Jooste & Rossouw (2002).

The database used

For water quality (salts and toxics) the ECOTOX database maintained by the USEPA (http://www.epa.gov/ecotox) was considered the most extensive and most accessible. All toxicity data were extracted. The database was not expanded to include results obtained with South African species. Care was exercised to ensure representation of toxicity data for: a) fish, b) other aquatic vertebrates, c) invertebrates, d) plants (no distinction was made between vascular plants and algae).

Where sufficient LC50 data at various exposure times were available an estimate of the LC50 at 2 weeks of exposure was made. The actual data and projection techniques appear in Jooste & Rossouw (2002).

A value for TDS is not included in the specifications for the water quality Reserve. While it is recognized that there are important biotic effects related to high composite salt concentrations, there is evidence that the effects of individual salts will outweigh the effects attributable to TDS. For this reason individual salts have been specified. The concentration of salts is calculated from ionic data (In the final manual there will be a reference to a DWAF web-site where a spreadsheet with the calculations can be down-loaded). A method for using TDS/EC as an end-point is under development.

1.2.2 Conditions for using this variable

Obligatory group of variables. This is a standard water quality Reserve group of variables and must always be considered.

1.2.3 Benchmarks

The benchmark table (Table 1) has been derived from an interpolation of the hazard-based stressor response curve generated from two radical points: the lethality benchmark and the sub-lethality benchmark (See additional information). The hazard was characterised in terms of the likelihood of loss of species expressed on a scale of 0 (unlikely) to 1 (very likely). Table 1 is the benchmark table for major inorganic salts which are listed in decreasing toxicity.

Table 1 The default benchmark category boundaries for inorganic salts

Variables	**Natural boundary (mg/l)**	**Good boundary (mg/l)**	**Fair boundary (mg/l)**
$MgSO_4$	16	27	37
Na_2SO_4	20	36	51
$MgCl_2$	15	33	51
$CaCl_2$	21	63	105
NaCl	45	217	389
$CaSO_4$	351	773	1195

1.2.4 Reference conditions

The Reference condition for salinity components is derived from sites that are known to have a high biotic integrity and that would be known to correspond to the description of a Natural site or one at which there is solid evidence that there is no significant anthropogenic impact.

If no inorganic salts data are available

- Use the default Natural boundary values in Table 1.

If inorganic salts data are available

For a medium confidence determination

- Refer to the default Natural boundary values in Table 1.
- Confirm that the reference site is largely natural and unimpacted by examining the response variables.
- Use a minimum of 25* samples collected over a 1-3 year period at an unimpacted site, including wet and dry seasons, to calculate the 95^{th} percentile concentrations. Compare the calculated 95^{th} percentile values to the default Natural boundary values in Table 1. If the 95^{th} percentile values are higher than the default Natural boundary values, then calibrate the default benchmarks as follows:
  - o move the default Natural boundary value for each salt to the value of the 95^{th} percentile concentration of the reference data. This is the new Natural boundary, and is used to calibrate the Good boundary.
  - o Move the Good boundary by half the amount by which the Natural boundary was changed, or in other words [Good = (Fair - Calibrated Natural) x 0.5 + Calibrated Natural].
- Calculate the confidence in the data as described in Jooste & Rossouw (2002) to determine the confidence in the present day assessment.
- * - Note that 25 samples is the minimum number of samples required to yield a power statistic of between 0.6 and 0.8 which is regarded as medium confidence.

For a high confidence determination

- Refer to the default Natural boundary values in Table 1.
- Confirm that the reference site is largely natural and unimpacted by examining the response variables.
- Use a minimum of 60* samples collected over a 3 year period at an unimpacted site, including wet and dry seasons, to calculate the 95th percentile concentrations. Compare the 95th percentile values to the default Natural boundary values in Table 1. If the 95th percentile values are higher than the default Natural boundary values, then calibrate the default benchmarks as follows:
    - o move the default Natural boundary value for each salt concentration to the value of the 95th percentile concentration of the reference data. This is the new Natural boundary, and is used to calibrate the Good boundary.
    - o Move the Good boundary by half the amount by which the Natural boundary was changed, or in other words [Good = (Fair - Calibrated Natural) x 0.5 + Calibrated Natural].
- Calculate the confidence in the data as described in Jooste & Rossouw (2002) to determine the confidence in the present day assessment.

* - Note that 60 samples are the minimum number of samples that would yield a power statistic greater than 0.8 which is regarded as high confidence.

1.2.5 Present state classification

The present state is assessed by calculating the 95th percentiles of the hazard for each salt. This calculation is automated within the SPATSIM software.

SPATSIM automates the following for each data record:

1. For each data record: Convert all relevant ionic data to units of millimoles/l. This is accomplished by dividing the concentration in mg/l by the ionic atomic or molecular mass (Na = 23; Mg=24.3; Ca = 40; Cl = 35.5; SO_4 = 96).
2. For each record, calculate the salts concentration in mM from the ionic concentrations in mM, as shown in Table 2.

Table 2 Formulae for the calculation of TIMS from ionic concentrations in millimoles/litre units

Salt (mM)	Calculation
$MgSO_4$	Minimum {Mg, SO_4}
Na_2SO_4	Minimum {Na/2, (SO_4 - $MgSO_4$)}
$MgCl_2$	Minimum {(Mg – $MgSO_4$), Cl/2}
$CaCl_2$	Minimum {Ca, (Cl - 2*$MgCl_2$)/2}
NaCl	Minimum {(Na – 2*Na_2SO_4), (Cl – 2*$MgCl_2$ – 2*$CaCl_2$)}
$CaSO_4$	Minimum {(Ca – $CaCl_2$), (SO_4 – $MgSO_4$ – Na_2SO_4)}

3. For each data record: Calculate the hazard for each salt by using the formula

$$y = 1/ (1+axe^{-bx})$$

where y is the hazard for a specific salt
X is the concentration of a specific salt in mM/L
a and b are parameters from Table 5a in Jooste & Rossouw (2002).

4. Calculate the 95th percentile of each salt in mM/L and their hazards using suitable statistical software.

5. Convert the 95th percentile salt values in mM/L to concentrations in mg/l by multiplying by the associated formula mass of the salts in Table 3.

Table 3 Formula mass of TIMS salts

Salt (mM)	Formula mass	Salt (mM)	Formula mass
$MgSO_4$	120.3	$CaCl_2$	111
Na_2SO_4	142	NaCl	58.5
$MgCl_2$	95.3	$CaSO_4$	136

6. Classify the hazard posed by the salts by comparing the 95th percentile of the calculated hazards to the value in Table 5c of Jooste & Rossouw (2002).

7. Use the power statistic calculated in Step 3 of the water quality Reserve process to determine the confidence of the present state classification.

8. Each salt is assigned a category and reported as such.

In special cases, the salt concentration to category relationship method of Scherman et al. (2003) and DWAF (2000) is useful, particularly for the assessment of the Good and Fair boundaries. Salt category boundaries established using this method have been found to relate well to SASS-category relationships.

All the category-salt concentration relationships used in this manual relate only to concentration, and do not take account of seasonality. Other than a somewhat conservative assumption of 2 weeks of exposure at the lethality benchmarks the duration of exposure to concentrations is not addressed. Methods are being developed to take account of the duration and frequency of concentrations. (Malan & Day, 2002)

1.2.6 Ecological specifications

The Ecological specifications are read off the calibrated benchmark boundary table (or the default benchmark boundary table if no adjustments were made).

1.2.7 Additional information

Calculating the theoretical salt content of a water sample

This procedure is described in the technical support document (Jooste & Rossouw, 2002). It is comprised of composing theoretical ion associations corresponding to major salts in a specific order dictated by the toxicity of these salts (expressed on a molar basis).

Background: the concept of a Toxicologically Important Major Salt

The data on which the benchmarks are based were derived from experiments where a population is exposed to a salt solution. For the most part, the salt will exist in solution as ions stabilised by water molecules. When a second salt is added, the same process occurs. Two possibilities now exist: either the organism reacts to the individual salts or it reacts to a macro characteristic of the water such as the osmolality. For the present, until more information on mixture toxicity is available, it is assumed that organisms react to concentrations of the virtual or theoretical salts it perceives in its environment.

This means, for example, that although initially there may only have been sodium and chloride in solution, the addition of a small amount of calcium sulphate (both of which are relatively non-hazardous) may give rise to a situation where an organism in the water perceives sodium sulphate in its environment. The resulting "virtual" sodium sulphate only depends on the limiting ion (probably sulphate in this case) and the ionic ratio sodium:sulphate.

From the example above it is clear that this "virtual" or toxicologically important salt may never actually have been discharged into the system. Its existence does not depend on any specific discharge, but rather on the combination that exists in the water sample.

The key to the assessment of salinity is, therefore, the calculation of these toxicologically important major salts (TIMS). It should be stressed that at its most fundamental level this is not a calculation of chemical equilibria but something more like a salt toxicity index.

Toxicologically Important Major Salts (TIMS) Calculation Procedure

Since the calculation deals with toxicologically important salts, the most toxic salts, i.e. those with the lowest molar benchmark values, are calculated first. The order in which the salts are composed is given in Table 2.

The lethality benchmark

The lethality benchmark has been calculated as the 5th percentile of the LC50 (336) dataset. Ideally this would be a non-parametric estimate of the percentile. Values are shown in Table 4.

Table 4 Stressor response benchmarks for major salts based on 95% protection of species. The order of toxicity based on molar concentration increases from top to bottom in the table.

Salt	Sub lethal (mg/l)	Lethal (mg/l)
$MgSO_4$	16	37
Na_2SO_4	20	51
$MgCl_2$	15	51
$CaCl_2$	21	105
NaCl	45	389
$CaSO_4$	351	1 195

This benchmark indicates the level at which less than 95% of all (theoretical) organisms will be protected from significant mortality and corresponds to a very high hazard.

The sub-lethality benchmark

The sub-lethality benchmark has been set at the 5th percentile of all the sub-lethal data available. This should be a non-parametric estimate of the percentile. Where insufficient sub-lethal data exist, the average ratio of 5th percentiles of sub-lethal to lethal data is used to calculate the sub-lethal benchmark.

This benchmark indicates the level at which it is expected that 95% of all (theoretical) organisms will be protected from sub-lethal effects and corresponds to a very low hazard.

Calculating the Benchmark Table

The benchmark table is generated from an S-shaped curve that is assumed to describe the hazard as a function of salt concentration. The curve is derived such that the sublethal benchmark yields a response (hazard) of 0.01 and the lethal benchmark yield a response of 0.99. These benchmarks also defines the upper boundaries of the “Natural” and “Fair” categories. The “Good” upper boundary is derived by interpolation.

The Natural boundary values correspond approximately to the CEVs (Chronic Effects Values) in the South African Water Quality Guidelines (DWAF, 1996) while the Fair boundary values correspond approximately to the AEVs (Acute Effects Values).

An Excel spreadsheet to calculate the salt concentrations is available on the IWQS web site (http://www.dwaf.gov.za/iwqs/iwqso/ecorivreserve.htm). The detail of the procedure appears in the technical support document (Jooste & Rossouw, 2002).

1.2.8 References

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1.3 NUTRIENTS

1.3.1 Rationale

Phosphate (PO_4^{-3}) and the total inorganic nitrogen (TIN)

Phosphorus can occur in numerous organic and inorganic forms, and may be present in waters as dissolved and particulate species. Phosphorus is an essential macro nutrient, and is accumulated by a variety of living organisms. Soluble orthophosphate is the only form that can be used by aquatic organisms. It has a major role in the building of nucleic acids and in the energy production of cells. In un-impacted river systems, phosphorus is readily taken out of solution and used by plants. In addition, the adsorption of phosphorus onto inorganic particles also results in an apparent "scavenging" of phosphorus and reduction in concentration. Phosphorus is considered to be the principal nutrient controlling the degree of eutrophication in aquatic ecosystems.

The flow regime of a river plays an important role in the mobility, availability and spatial distribution of phosphorus. In un-impacted freshwater systems, phosphorus concentrations are generally low ranging between 5 and 50 g/ . Settlement of particulate matter and biotic uptake reduces the concentration of phosphorus in the water column of a river and increases the concentration of P in sediments. During periods of high river flow, there is considerable increase in the phosphorus concentration of the river as a result of phosphorus scoured from the stream bed as well as inflow of nutrient laden water from surrounding catchment areas and changes in exchange sites on the transported sediment material.

Elevated phosphorus concentrations in a river may result from point source discharges (i.e. municipal and industrial effluents) and diffuse source runoff (i.e. agricultural and urban runoff). Where point and diffuse runoff discharge into a river a number of changes in the concentration of the various phosphorus species occur; these include:

- an increase in the orthophosphate and total phosphorus concentration;
- a shift in the soluble to particulate phosphorus ratio, with an increasing proportion of soluble phosphorus near the point of discharge. In the downstream reaches, there will be a shift back from the soluble to the particulate form.

The term inorganic nitrogen includes all the major inorganic nitrogen components (NH_3^+ + $NH4^+$ + NO_2^- + NO_3^-) present in water. Both the dissolved forms of inorganic nitrogen and those adsorbed onto suspended inorganic and organic material are included, since they are all available for uptake by algae and higher plants.

Ammonia (NH_3^+) and ammonium (NH_4^+) are reduced forms of inorganic nitrogen and their relative proportions are controlled by water temperature and pH. Both forms can exist as dissolved ions, or can be adsorbed onto suspended material.

Nitrite (NO_2^-) is the inorganic intermediate, and nitrate (NO_3^-) the end product, of the oxidation of organic nitrogen and ammonia. Nitrate is the more stable of the two forms and is usually far more abundant in the aquatic environment. In view of their co-occurrence and rapid inter-conversion, nitrite and nitrate are usually measured and considered together.

Inter-conversions between the different forms of inorganic nitrogen are part of the nitrogen cycle in aquatic ecosystems.

Inorganic nitrogen is primarily of concern due to its stimulatory effect on aquatic plant growth and algae. Most aquatic organisms are sensitive to the toxic effects of ammonia. See guideline for ammonia.

Site-specific conditions, especially the availability of phosphorus, are critically important in modifying the influence of inorganic nitrogen on eutrophication. Inorganic nitrogen toxicity is not considered to be important for setting inorganic nitrogen water quality guidelines for protection of aquatic ecosystems.

Inorganic nitrogen concentrations below 0.5 mg N/ℓ are considered to be sufficiently low that they can limit eutrophication and reduce the likelihood of nuisance growths of blue-green algae and other plants. However, in the presence of sufficient available phosphorus, nitrogen-fixing organisms will be able to fix atmospheric nitrogen, thereby compensating for any deficit caused by low inorganic nitrogen concentrations.

1.3.2 Conditions for using this variable

Obligatory group of variables. This is a standard water quality Reserve group of variables and must always be considered.

1.3.3 Benchmarks

Table 5 The default benchmark category boundaries for median nutrients concentrations. The SRP concentration should be used as the driver in the reference condition.

Category	Median Soluble Reactive Phosphorus, SRP, mg/ℓ	Median Total Inorganic Nitrogen, TIN, (Nitrate + Nitrite + Ammonia), mg/ℓ
Natural	<=0.005	<=0.25
Good	0.0051 - 0.025	0.251 – 1.0
Fair	0.0251 - 0.125	1.01 – 4.0
Poor	>0.125	>4.0

- The median concentration should be used to determine the category (Table 5).
- The SA Water Quality Guidelines for Aquatic Ecosystems (DWAF, 1996), the Umgeni Water, Water Quality Index ranges and practical experience in the Umgeni Water Operation Area were considered in drawing up these ranges.

1.3.4 Reference conditions

If no nutrient data are available

- Use the Natural boundary values in Table 5.

If nutrient data are available

For a medium confidence determination

- Refer to the Natural boundary values in Table 5.
- Confirm that the reference site is largely natural and unimpacted by examining the response variables.
- Use a minimum of 25* samples collected over a 1-3 year period at an unimpacted site, including wet and dry seasons, to calculate the median concentrations. Compare the median values to the default Natural boundary values in Table 5. If the median value is higher than the default Natural boundary value, then calibrate the default benchmarks as follows:
  - o move the default Natural boundary value for SRP or TIN concentrations to the value of the median concentration of the reference data. This is the new Natural boundary, and is used to calibrate the Good boundary.
  - o Move the Good boundary by two times the amount by which the Natural boundary was changed, or in other words [Calibrated Good = Default Good + 2 x (Calibrated Natural – Default Natural)].
- Calculate the confidence in the data as described in Jooste & Rossouw (2002).
- * - Note that 25 samples is the minimum number of samples required to yield a power statistic of between 0.6 and 0.8 that is regarded as medium confidence.

For a high confidence determination

- Refer to the Natural boundary values in Table 5.
- Confirm that the reference site is largely natural and unimpacted by examining the response variables.
- Use a minimum of 60* samples collected over a 3 year period at an unimpacted site, including wet and dry seasons, to calculate the median concentrations. Compare the median values to the default Natural boundary values in Table 5. If the median value is higher than the default Natural boundary value, then calibrate the default benchmarks as follows:
  - o move the default Natural boundary value for SRP or TIN concentrations to the value of the median concentration of the reference data. This is the new Natural boundary, and is used to calibrate the Good boundary.
  - o Move the Good boundary by two times the amount by which the Natural boundary was changed, or in other words [Calibrated Good = Default Good + 2 x (Calibrated Natural – Default Natural)].
- Calculate the confidence in the data as described in Jooste & Rossouw (2002).
- * - Note that 60 samples are the minimum number of samples that would yield a power statistic greater than 0.8 that is regarded as high confidence.

1.3.5 Present state classification

No nutrient data are available

- Examine the response variables (refer to Biological Indicator of water quality, and Chlorophyll *a*) and/or use visual observations made during a site visit(s) to record a qualitative, expert judgement assessment of the present nutrient status. Provide adequate reasons for the assessment and rate the confidence as low.

If nutrient data are available

- Assemble the SRP and TIN data from the most recent 5 years of the data record.
- Calculate the median (50th percentile) of the SRP and TIN data.
- Compare the median concentrations to the default nutrient benchmark table (Table 5), or the calibrated nutrient benchmark table that was modified using reference data, and classify the present nutrient status.
- If the chlorophyll *a* category is poorer than the nutrient category and the reason for the poorer class can be traced to anthropogenic causes, then reduce the nutrient category by one class.
- Calculate the confidence in the SRP and TIN data sets as described in Jooste & Rossouw (2002) and, using the power statistic, express the confidence as low ($p<0.6$), medium ($0.6>p<0.8$) or high ($p>0.8$).
- Provide a qualitative statement expressing your confidence in the data set to represent the spatial and temporal nutrient status of the whole resource unit.

1.3.6 Ecological specifications

The Ecological specifications are read off the calibrated nutrient benchmark boundary table (or the default nutrient benchmark boundary table if no adjustments were made).

1.3.7 Additional information

Sample preservation

The nutrient concentrations in samples can change if the water samples are not preserved before it is submitted to the laboratory. For example, algae growing in the sample bottle can result in lower dissolved nutrient fractions and higher particulate fractions. The preservation status is generally recorded in the water quality database. The user should be cautious about using the nutrient data from unpreserved samples especially for characterising a reference site.

Total versus dissolved nutrient fractions

Dodds (2003) cautions against using total inorganic N and soluble reactive P to indicate the trophic status of river water. Measurements of total N (TN) and total P (TP) represent the total nutrient content actually in biomass or available for incorporation into biomass. These measurements are therefore often used to determine the trophic status. The TN to TP ratio (TN:TP) is often used to indicate nutrient deficiency because it correlates well with other measures of nutrient deficiency such as growth-based bioassays. He found that DIN:SRP is a poor surrogate for TN:TP and cautioned against its use to indicate nutrient limitation.

However, TN and TP are not commonly recorded in South African rivers which is why the current methodology only considers TIN and SRP. Benchmarks for TN and TP and for the TIN:TP ratio will be developed during the next round of revisions to the water quality methods.

Example: Modifying the default benchmark table

If the median concentration at an unimpacted reference site is higher than the default Natural boundary value, then the default Natural benchmark is modified by making it equal to the reference concentration. The default Good boundary is changed by adding two times the amount by which the Natural boundary has changed, or in other words [Calibrated Good = Default Good + 2 x (Calibrated Natural – Default Natural)]. The fair boundary remains unchanged.

For example: if the median SRP concentration at the reference site is 0.008 mg/l, then the calibrated Natural boundary is equal to 0.008 mg/l and the calibrated good boundary is:
Calibrated Good = 0.025 + 2x(0.008-0.005) = 0.025 + 0.006 = 0.031 mg/l

The new benchmark table for SRP should look as follows:

Category	Natural	Good	Fair	Poor
Default benchmarks	<0.005	0.005 - 0.025	0.025 - 0.125	> 0.125
Modified benchmarks	<0.008	0.008 – 0.031	0.031 – 0.125	> 0.125

1.3.8 References

DWAF (1996) South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems. Second Edition. Department of Water Affairs and Forestry, Pretoria, South Africa.

Dodds, W (2003) Misuse of inorganic N and soluble reactive P concentrations to indicate nutrient status of surface waters. **Journal of the North Amercian Benthological Society**, 22(2), 171-181.

Jooste, S & Rossouw, JN (2002) Hazard-based Water Quality EcoSpecs for the Ecological Reserve in Fresh Surface Water Resources. Report No N/0000/REQ0000. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

1.4 DISSOLVED OXYGEN

1.4.1 Rationale

Oxygen dissolves in water and is also generated during photosynthesis by aquatic plants. Oxygen is soluble in water but varies inversely with increasing water temperature. The maintenance of adequate dissolved oxygen concentrations is critical for the survival and functioning of aquatic biota because of their respiration needs. Therefore, DO provide a measure of the health of an aquatic system.

The sensitivity of many species, especially fish and invertebrates, to changes in dissolved oxygen concentrations depends on the species and the life stages (eggs, larvae or adult) and behavioral changes (feeding and reproduction). Juveniles of many aquatic organisms are more sensitive to physiological stress arising from oxygen depletion, and in particular to secondary effects such as increased vulnerability to predation and disease. Where possible, many species will avoid anoxic or oxygen-depleted zones.

Cold-water-adapted species such as salmonids (e.g., trout) are especially sensitive to depletion of dissolved oxygen. Reproduction and growth in these species is reduced under continuous exposure to oxygen concentrations less than 100 % saturation.

Oxygen concentrations above saturation may cause gas bubble disease in fish. Super-saturated conditions also tend to inhibit photosynthesis in green algae, favouring instead blue-green algae, which are more tolerant of super-saturation, but which may become a nuisance to other water users.

The reversibility of toxic effects on organisms depends on the duration, frequency and timing of the occurrence of oxygen depletion. Physiological stress effects in adult or less sensitive life stages may be rapidly reversed if oxygen depletion is short-lived. Prolonged exposure of aquatic communities to dissolved oxygen concentrations less than 50 % of saturation can cause significant changes in community composition, as more tolerant species are favoured.

High water temperatures combined with low dissolved oxygen levels can compound stress effects on aquatic organisms. The depletion of dissolved oxygen in conjunction with the presence of toxic substances can also lead to a compounded stress response in aquatic organisms. Under such conditions increased toxicity of zinc, lead, copper, cyanide, sulphide and ammonia have been observed.

1.4.2 Conditions for using this variable

Obligatory variable. This is a standard water quality Reserve variable and must always be considered.

1.4.3 Benchmarks

The default benchmark category boundaries for dissolved oxygen (Jooste & Rossouw, 2002) are presented in Table 6.

Table 6 The default benchmark category boundaries for dissolved oxygen (mg/l)

Category	Dissolved oxygen
Good	6mg/l @25^{o}C
Fair	4 mg/l @25^{o}C

Currently the default benchmark table has no Natural boundary. The good and fair boundaries are physiological boundaries that should not be changed.

1.4.4 Reference conditions

If no dissolved oxygen data are available

- Use the Natural boundary values in Table 6 directly.
- If a high confidence assessment is a requirement of the determination, then design and implement a dissolved oxygen monitoring programme at the reference and PES sites.

If dissolved oxygen data are available

- Confirm that the reference site is largely natural and unimpacted by examining the response variables.
- Calculate the 5th percentile concentration of the reference data to set the Natural boundary. If the calculated Natural boundary is less than 6 mg/l, then use default benchmark boundary values (Table 6).

1.4.5 Present state classification

If dissolved oxygen data are not available

- Use visual observations made during a site visit(s) to record a qualitative, expert judgement of the present dissolved oxygen status. Provide adequate reasons for the assessment and rate the confidence as low.

If dissolved oxygen data are available

- Calculate the 5th percentile of the PES data and compare to the default values in Table 6 or to the calibrated values.

1.4.6 Ecological specifications

The Ecological specifications are read off the default dissolved oxygen benchmark boundary table if no adjustments were made (or the calibrated dissolved oxygen benchmark boundary table if adjustments were made).

1.4.7 Additional information

Dissolved oxygen measurement

Where possible, measure % saturation in the early morning at a reference site. All oxygen data can be used, but qualifying information such as time of day and organic pollution are important to note.

1.4.8 References

Jooste, S & Rossouw, JN (2002) Hazard-based Water Quality EcoSpecs for the Ecological Reserve in Fresh Surface Water Resources. Report No N/0000/REQ0000. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

1.5 pH

1.5.1 Rationale

The equilibrium between acid and base/alkali in water is a fundamental characteristic that influences not only the chemistry of the water, but also the physiology of the organisms in the water. In the present context, an acid refers to the Brønsted-Lowry definition of an acid, which is a substance that releases hydrogen ions (H^+) into water. In water H^+ does not normally exist in that form, but forms a hydronium ion (H_3O^+) in reaction with water. On the other hand, a Brønsted-Lowry base is a substance that binds H^+ and in aqueous reaction this would result in a net production of the hydroxyl (OH^-) ion. Typically basic condition in aquatic systems may be brought about by alkalis such as the hydroxides or carbonates of sodium or potassium (alkali metals) or calcium or magnesium (alkaline earth metals).

Background

The water quality guidelines for aquatic ecosystems state the target water quality range should not vary from the background by greater than 0.5 of a pH unit, or by greater than 5 percent and should be assessed by whichever estimate is the more conservative (DWAF, 1996).

Dallas and Day (1993) state that changes in the pH of a river can have severe effects on the biota, but it should also be noted that many streams may be naturally acidic or basic. Thus, there is no pH range that is suitable for all streams and guidelines should be site specific. It was also noted that in poorly buffered waters (as found in the Western Cape) the pH could change dramatically. Dallas and Day (1993) suggest that the pH should not change by more than one pH unit.

Effect of pH

Acidity or basicity in water may have an impact on biota through three broad mechanistic routes: physical integrity of the organisms, direct impact on the physiology of the biota in the water, and indirect impact through the chemistry of the water. The effect boundaries for these mechanisms vary widely. Of these, the physiological effect boundaries are probably the narrowest, but it is difficult to establish the hazard gradation with the same level of accuracy as was the case with specific substances. The clearest information was found in the ANZECC draft guidelines (1999) and Alabaster and Lloyd (1982). Given the paucity of information, it was decided that for a generic response relationship to use the most conservative range in these sources for the sub-lethal benchmark and the widest range as the lethality benchmark. The default benchmarks are listed in Table 7.

1.5.2 Conditions for using this variable

Compulsory variable for all water quality reserve determinations.

1.5.3 Benchmarks

Table 7 The default benchmark category boundaries for pH

Category	pH
Natural	6.5 – 8.0
Good	5.75-6.46 and 8.05-9.00
Fair	5.00-5.70 and 9.05-10.00
Poor	<5.00 or >10.00

1.5.4 Reference conditions

If no pH data are available

- Use the Natural boundary values in Table 7.

If pH data are available

The Reference condition for pH is derived by calculating the 5th and 95th percentiles of pH data from a site that is known to have a high biotic integrity and that would be known to correspond to the description of a Natural site or one at which there is solid evidence that there is no significant anthropogenic impact.

If the data fall within the "Natural" boundary values

- If the 5th and 95th percentiles of the reference data fall within the default "Natural" range, then use the default benchmark table (Table 7) to assess the present state.

If the data outside the "Natural" boundary values

The pH of some mountain streams originating in granite or sandstone and which drains forest areas may have naturally low pH values. Likewise, conditions may exist that result in a naturally high pH. If sufficient evidence exist that a specific reference site has pH values that will classify it as anything but "Natural" then the default pH benchmarks should be adjusted. The adjustment pre-conditions are:

IF

- The 5th percentile of the pH data of a site that is considered practically pristine or for which bio assessments indicate a sustained good integrity over a period of at least three years is lower than the lower "Natural" benchmark in Table 7,

OR

- The 95th percentile of the pH data of a site that is considered practically pristine or for which bio assessments indicate a sustained good integrity over a period of at least three years is higher than the upper "Natural" benchmark in Table 7,

THEN

- Replace the lower "Natural" benchmark with the 5th percentile of the reference dataset and replace the lower "Fair" benchmark with the new benchmark = old benchmark – 1.5, and calculate the "Good" boundary as the mean of the "Natural" and "Fair" boundary values.

OR

- Replace the upper "Natural" benchmark with the 95th percentile of the reference dataset and replace the upper "Fair" benchmark with the new sub-lethality benchmark = old sub-lethality benchmark + 1 and calculate the "Good" boundary as the mean of the "Natural" and "Fair" boundary values.

Express the results of the calibrated pH benchmark table as shown in Table 7.

1.5.5 Present state classification

The present state is classified by comparing the 5^{th} and 95^{th} percentiles of the data set to the upper and lower benchmarks in Table 7 or the calibrated pH benchmark table.

If the categories identified by the 5^{th} and 95^{th} percentiles are not the same, select the poorest (worst) category to classify the present state.

1.5.6 Ecological specifications

The Ecological specifications are read off the calibrated pH benchmark boundary table (or the default pH benchmark boundary table if no adjustments were made).

1.5.7 Additional information

Change in the DWAF pH determination method

In 1988/89 the DWAF method for pH determination was changed. This has resulted in DWAF pH values recorded after 1988/89 being on average about 0.5 pH units higher than before the change. Users are cautioned against using DWAF pH data from before 1988/89 to characterise reference conditions and then comparing it to pH data recorded in recent times to characterise the present status. It is preferable to identify an unimpacted reference site and to use pH data recorded after 1988/89 to characterise reference conditions. There are currently no guidelines for resolving the discontinuity in pH data when DWAF changed the determination method. It is recommended that users use scatter plots to examine the pH data set and use expert judgement if a comparison is required between pre- and post-1988/89 pH data.

1.5.8 References

ANZECC (1999) Australian and New Zealand Guidelines for fresh and marine Water Quality Volume 2: Aquatic Ecosystems – rationale and background information (Chapter 9). Australia and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand.

Alabaster, JS & Lloyd, R (1982) **Water Quality Criteria for Fresh Water Fish**, second edition. Butterworth Scientific, London.

DWAF (1996) The South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems. Second Edition. Department of Water Affairs and Forestry, Pretoria, South Africa.

Jooste, S & Rossouw, JN (2002) Hazard-based Water Quality EcoSpecs for the Ecological Reserve in Fresh Surface Water Resources. Report No N/0000/REQ0000. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

1.6 TURBIDITY

1.6.1 Rationale

Water turbidity in the southern hemisphere is generally considered to be equivalent to some measure of the concentration of suspended solids. Turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through a water sample. The scattering of light is caused by suspended matter such as clay, silt and finely divided organic material, while the absorption of light is caused by inorganic matter, plankton and other microscopic organisms and soluble coloured organic compounds, such as fulvic, humic and tannic acids.

In turbid waters light penetration is reduced, leading to a decrease in photosynthesis. The resultant decrease in primary production reduces food availability for aquatic organisms higher up the food chain. Suspended solids may interfere with the feeding mechanisms of filter-feeding organisms such as certain macroinvertebrates, and the gill functioning, foraging efficiency (due to visual disturbances) and growth of fish.

Suspended solids that settle out may smother or abrade benthic plants and animals, and may result in changes to the nature of the substratum. This may then lead to changes in the structure of the biotic community by the decline of these organisms, through the replacement with organisms which burrow in soft sediments. Sensitive species may be permanently eliminated if the source of the suspended solids is not removed.

The recovery of a stream from sediment deposition is dependent on the elimination of the sediment source and the potential for the deposited material to be flushed out by stream flow.

1.6.2 Conditions for using this variable

Optional variable.

Turbidity should be considered when there is good indication that land use practises such as overgrazing, contour ploughing, removal of riparian vegetation and forestry operations results in unnatural high loads of suspended sediments.

1.6.3 Benchmarks

TO BE COMPLETED.

Table 8 The benchmark category boundaries for turbidity

Category	**Turbidity**
Natural	UNDER DEVELOPMENT
Good	UNDER DEVELOPMENT
Fair	UNDER DEVELOPMENT

1.6.4 Reference conditions

UNDER DEVELOPMENT.

1.6.5 Present state classification

UNDER DEVELOPMENT.

Measure and report turbidity. Do not use data for classification until a category turbidity relationship has been developed.

1.6.6 Ecological specifications

UNDER DEVELOPMENT

1.6.7 Additional information

UNDER DEVELOPMENT.

1.6.8 References

TO BE COMPLETED.

1.7 TEMPERATURE

1.7.1 Rationale

At any point in a river system, the water temperature will vary over an hourly, daily and seasonal basis. The range in water temperature variation is the result of numerous natural factors such as source inflow from snow melts and ground water, the altitude and latitude of the river, as well as the local climate such as air temperature, cloud cover, and wind speed. Heat exchange studies performed on a number of South African rivers show that the variation in summer mean daily water temperature can range between -3 to +6 °C around the summer mean value.

Dallas and Day (1993) state that a change in water temperature may have an effect on aquatic organisms but the extent and timing of the change will dictate the overall impact. Establishing suitable temperature criteria is difficult in view of the differences in temperature tolerances of the biota, and because of the large variation in rivers. Tarzwell (1970) recommended a maximum increase of 2.8 °C be allowed in rivers, that temperatures should never exceed the maximum limits of the biota, and that no heated effluents must be allowed into spawning areas. Dallas and Day (1993) suggest a maximum temperature increase or decrease of 10 percent of the original water temperature prior to perturbation.

The water quality guidelines for aquatic ecosystems (DWAF, 1996) suggest a target water quality range of 2 °C or by 10 percent (whichever estimate is the more sensitive).

The approach used to specify the benchmarks for temperature was to estimate the natural distribution of temperature in the water quality resource unit. This is done by specifying a monthly temperature range, characterised by the 10^{th} and 90^{th} percentile temperatures for each month. Temperatures outside the natural range are regarded as indicative of impacts and the larger the deviation from the natural range, the poorer the state of the river (Table 9).

1.7.2 Conditions for using this variable

Optional variable.

Temperature should only be considered if there is evidence of thermal impacts, for example, below dams with bottom-release valves, inter-basin transfers or downstream of thermal effluents. Temperature is evaluated as a site-specific deviation from the natural temperature range.

1.7.3 Benchmarks

Table 9 The benchmark category boundary descriptions for temperature

Category	Temperature
Natural range	Monthly 10th and 90th percentiles of observed reference data or simulated reference temperature data
Good range	Upper boundary = 90th percentile + minimum(0.1*90th percentile, 2 °C) Lower boundary = 10th percentile - minimum(0.1*10th percentile, 2 °C)
Fair range	Upper boundary = 90th percentile + minimum(0.2*90th percentile, 4 °C) Lower boundary = 10th percentile - minimum(0.2*10th percentile, 4 °C)

1.7.4 Reference conditions

If observed data are available for reference conditions

- Standardize the temperature to 12:00
- Sort the temperature database by month.
- Calculate the 10th and 90th percentiles for each month. This represents the natural reference temperature range for each month (Figure 1).
- Calculate the upper and lower boundaries of the good and fair categories using the approach described in Table 9 and summarize the results in the benchmark table.

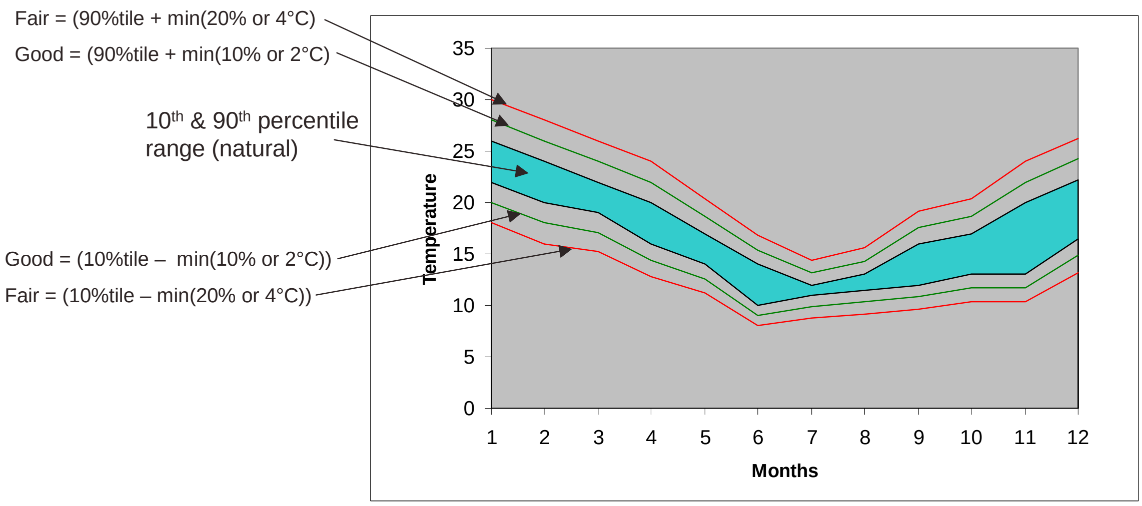

Figure 1 Natural monthly reference temperature range.

If no observed data are available

For a low confidence assessment (Rapid reserve)

- Calculate the mean monthly water temperature distribution using a simple model (e.g. Van Schalkwyk & Walmsley, 1984).
- Set the 10th and 90th percentiles for each month by adding or subtracting 2 °C from the monthly mean value.
- Calculate the upper and lower boundaries of the good and fair categories using the approach described in Table 9.

For a medium confidence assessment (Intermediate reserve)

- Calculate daily water temperatures from daily air temperatures using an empirical relationship between air temperature and water temperature (e.g. Stefan & Preud'homme, 1993 or Pilgrim *et al*., 1998).
- Sort the estimated daily water temperatures by month and calculate the 10th and 90th percentiles for each month.
- Calculate the upper and lower boundaries of the good and fair categoryes using the approach described in Table 9.

For a high confidence assessment (Comprehensive reserve)

- Calculate daily water temperatures using a locally calibrated empirical relationship between air temperature and water temperature (e.g. Stefan & Preud'homme, 1993, Pilgrim *et al*., 1998) or if resources are available, a deterministic stream temperature model (e.g. Bartholow, 2002).
- Sort the estimated water temperatures by month and calculate the 10th and 90th percentiles for each month.
- Calculate the upper and lower boundaries of the good and fair categories using the approach described in Table 9 and summarize the results in the benchmark table.

1.7.5 Present state classification

The present state can only be classified if observed temperature data are available.

If observed data are available to classify the present state

- Sort the temperature database by month.
- Calculate the 10th and 90th percentiles for each month. This represents the present state temperature range for each month (Figure 2).
- Compare the 10th and 90th percentiles to the natural, good and fair boundaries for the reference site and assign a category to each value. The present state category for the month is the poorest category obtained when comparing the 10th or the 90th percentile to the reference site for a specific month (see the example below).

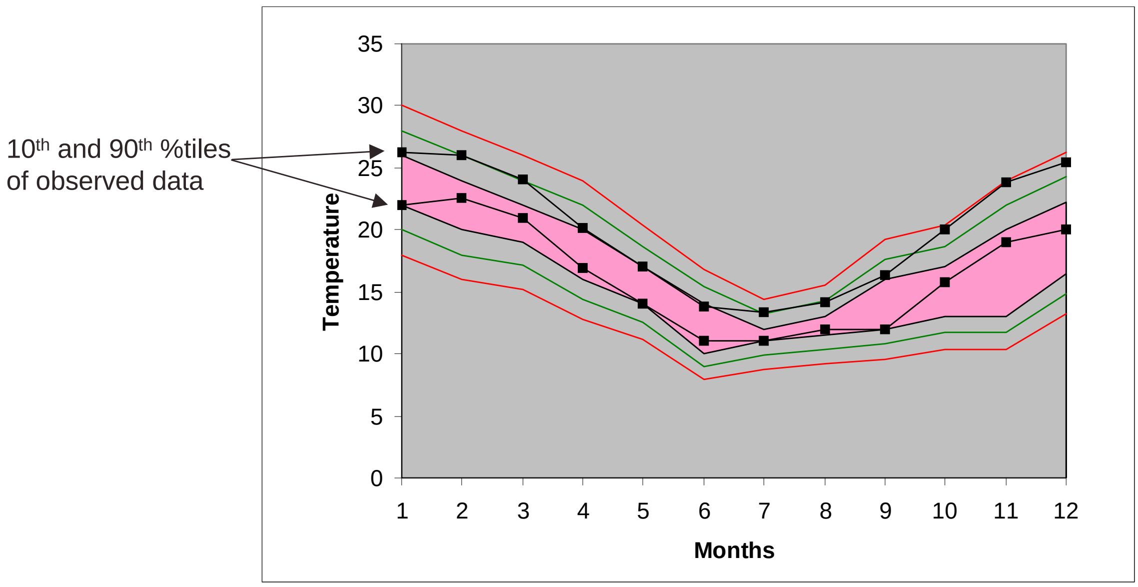

Figure 2 Present state monthly temperature range.

If no observed data are available to classify the present state

- Design a monitoring programme to collect data over at least one seasonal cycle and use the observed data to classify the present state as described in the previous section.

1.7.6 Ecological specifications

Specify the monthly upper and lower water temperature boundaries for the natural, good, fair and poor categories based on the 10th and 90th percentile temperatures at the reference site (see example below).

Example

Calendar month	1	2	3	4	5	6	7	8	9	10	11	12
Upper Fair boundary	30	28	26	24	20.4	16.8	14.4	15.6	19.2	20.4	24	26.25
Upper Good boundary	28	26	24	22	18.7	15.4	13.2	14.3	17.6	18.7	22	24.25
Upper natural boundary	26	24	22	20	17	14	12	13	16	17	20	22.25
Lower natural boundary	22	20	19	16	14	10	11	11.5	12	13	13	16.5
Lower good boundary	20	18	17.1	14.4	12.6	9	9.9	10.35	10.8	11.7	11.7	14.85
Lower fair boundary	18	16	15.2	12.8	11.2	8	8.8	9.2	9.6	10.4	10.4	13.2

1.7.7 Additional information

A Water Research Commission project by N. Rivers-Moore of the University of Natal (Pietermarizburg) is under way to develop a stream water temperature model for South African conditions. Daily maximum water temperatures were modelled using statistical approaches that incorporate air temperatures as the principal surrogate for water temperatures. Multiple linear regression models were the most pragmatic approach to simulate ecologically important water temperatures within the Sabie River. The usefulness of such models as a management tool was enhanced by the inclusion of a flow-dependant term, since this provides the potential to consider the impacts of impoundments and climate change on water temperatures using, amongst other, ambient air temperature and discharge, as input. This project is due for completion in 2003.

1.7.8 References

Bartholow, JM (2002) SSTEMP for Windows: The stream segment temperature model (Version 2.0). US Geological Survey computer model and documentation. Available on the Internet at http://www.fort.usgs.gov/

Dallas, HF & Day, JA (1993) **The effect of water quality variables on riverine ecosystems: A review.** Water Research Commission, Report TT61/93, Pretoria, South Africa.

DWAF (1996) South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems. Second Edition. Department of Water Affairs & Forestry, Pretoria, South Africa.

Pilgrim, JM, Fang, X & Stefan, HG (1998) Stream temperature correlations with air temperatures in Minnesota: Implications for climate warming. **Journal of the American Water Resources Association**, 34(5), 1109-1121.

Rivers-Moore, NA (2003) *Water temperature and fish distribution in the Sabie River system: Towards the development of an adaptive management tool.* PhD Thesis, University of Natal, Pietermaritzburg, South Africa.

Stefan, HG & Preud'homme, EB (1993) Stream temperature estimation from air temperature. **Water Resources Bulletin**, 29(1), 27-45.

Tarzwell, CM (1970) Thermal requirements to protect aquatic life. **Journal of the Water Pollution Control Federation**, 42, 824-828.

Van Schalkwyk, DJ & Walmsley, RD (1984) Prediction of surface water temperature of South African impoundments. **Journal of the Limnological Society of Southern Africa**, 10(2): 57-61.

41.8 TOXIC SUBSTANCES

1.8.1 Rationale

Toxic substances: Those listed in the South African Water Quality Guidelines for Aquatic Ecosystems (DWAF 1996), including toxic metal ions and toxic organic substances and/or substances selected from the chemical inventory of an effluent/discharge

1.8.2 Conditions for using this variable

Triggered by an inventory of chemical substances likely to be discharged or low biotic response (e.g. an anomalous SASS score).

1.8.3 Benchmarks

The benchmarks for toxic substances are defined by the South African Water Quality Guidelines (DWAF, 1996). The derivation procedures for the salinity benchmarks were largely modelled on the derivation procedures used in these guidelines. Table 10 lists the default benchmark values to be used for toxic substances.

Table 10 Benchmarks for some toxic substances as listed in DWAF (1996).

Substance	Natural (µg/l)	Good (µg/l)	Fair (µg/l)
Al	20	85	150
Ammonia	15	58	100
As	20	75	130
Atrazine	19	59	100
Cd soft*	0.2	1.0	1.8
Cd mod**	0.2	1.5	2.8
Cd hard***	0.3	2.7	5.0
Chorine (free)	0.4	2.7	5
Cr(III)	24	182	340
Cr(VI)	14	107	200
Cu soft*	0.5	1.1	1.6
Cu mod**	1.5	3.0	4.6
Cu hard***	2.4	5.0	7.5
Cyanide	4	57	110
Endosulfan	0.02	0.11	0.2
Fluoride	1500	2020	2540
Pb soft*	0.5	2.3	4
Pb mod**	1	4	7
Pb hard***	2	8	13
Hg	0.08	0.9	1.7
Phenol	60	280	500

*For use in soft water (Hardness less than 60mg $CaCO_3$/l)
** For use in moderately hard water (Hardness between 60 – 119 mg $CaCO_3$/l)
***For use in hard water (Hardness greater than 120 mg $CaCO_3$/l)

Benchmarks for toxic substances not listed in Table 10 should only be derived in consultation with appropriate DWAF officials.

1.8.4 Reference conditions

For the most part, toxic substances do not occur naturally, therefore for practical purposes the reference value is equal to the detection limit. The exceptions to this are some metals such as copper and chromium, semi-metals such as selenium and arsenic and non-metals such as fluoride.

In some situations it may be necessary to take into account naturally elevated background levels of these substances. The method for adjusting the default benchmark table for these toxic substances is the same as for inorganic salts.

1.8.5 Present state classification

Use data as specified in Table 10, and calculate the 95^{th} percentile. Compare this value with the default benchmark table (Table 10) and assign the class for toxic substances.

1.8.6 Ecological specifications

The Ecological specifications are read off the calibrated benchmark boundary table (or the default benchmark boundary table if no adjustments were made).

1.8.7 Additional information

Method to obtain the un-ionised ammonia concentration.

Un-ionised ammonia is dependent on the pH and the water temperature and can be derived from a table showing the relationship or can be calculated if the water temperature, pH and electrical conductivity (or TDS) is known. These methods are described in DWAF (1996).

Differences in terminology

The terms lethality benchmark and sub-lethality benchmark are specific to salts and are not found in the South African Water Quality Guidelines (DWAF, 1996). Apparently the equivalent terms used in these guidelines are acute effect value (AEV) and chronic effect value (CEV), but there are important differences:

- The lethal (critical) benchmark is approximately equivalent to the final acute value (FAV, DWAF, 1996 p 141) which is AEV*2. The rationale for the factor 2 was that many of the toxic substances might also have a much higher uptake rate than an excretion rate in most aquatic organisms (i.e. they have a tendency to accumulate in organisms). Specifying an AEV at half the FAV meant that even in the 5^{th} percentile of organisms a reasonable duration of exposure could be tolerated.
- The lethal benchmark is projected from LC50s at 336 hour of exposure while the AEVs were derived from acute toxicity data for which exposures differ from a few hours to 96 (or occasionally more) hours.

However, despite these differences, it was decided to use the AEV as the lethal (critical) benchmark to maintain continuity.

The derivation of the CEV and the chronic benchmark is practically identical, and so the benchmarks are used interchangeably.

1.8.8 References

DWAF (1996) South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems. Second Edition. Department of Water Affairs and Forestry, Pretoria, South Africa.

1.9 BIOLOGICAL INDICATOR OF WATER QUALITY

1.9.1 Rationale

SASS (South African Scoring System, Version 4, (Chutter 1998) and Version 5, (Dickens & Graham 2002) is a rapid bioassessment technique that is a well recognised measure of water quality and general river health. SASS makes use of the natural sensitivity or tolerance to adverse water quality, of the wide variety of benthic invertebrates in a river, aggregating the effects of water quality over time (several weeks). SASS thus provides an ideal system to measure the response of aquatic fauna to general water quality conditions in a river. The particular advantage of a biotic index is that the presence of chemical variables, not monitored by chemical analysis, which may have an impact on the river environment, can be detected. Although these may not be identifiable, this does prompt management action to identify and manage these variables. Note that the use of SASS in this protocol is as an indicator of river water quality and is not intended to fulfil the need to monitor biodiversity.

SASS was developed for running waters and should not be used for setting the Reserve of ephemeral rivers and standing waters. Nevertheless, where an ephemeral river has a strong flow for extended periods, it may be possible to determine the Reserve by confining the assessment and the allocation of the Reserve Class to the appropriate time of year. This will be an uncertain assessment and should be well documented.

The SASS method produces three different and complimentary scores, SASS Score, Number of Taxa and ASPT (Average Score per Taxon). While the Reserve procedure relies on ASPT, as this is the least variable of the scores (Dallas, 2000; Dickens & Graham, 2002) and also provides the most reliable measure of a Natural Class, the other two scores can be used to aid interpretation. For example, in “clean” rivers, ASPT gives more reliable results, while in “polluted” rivers, SASS Score may be more reliable (Chutter, 1998). There are also exceptional cases where, in polluted rivers, the ASPT score can be unreasonably high. In these cases the SASS Score will indicate the presence of pollution. If apparent anomalies such as this occurs during a Reserve assessment, it will be necessary to produce a thorough report giving evidence which can, in exceptional cases, be used to override the procedure below.

SASS is used in three ways to determine the Reserve. All three methods rely on Table 11 but have different levels of confidence, as described below. Table 11 provides the range of ASPT scores assigned to the Reserve Classes. While this allocation was made using 1500 SASS data sets collected over nearly 8 years by Umgeni Water, it is anticipated that exceptions will occur in some parts of the country. Procedures have been described below to take care of this eventuality.

1.9.2 Conditions for using this variable

Obligatory variable for low, medium and high confidence determinations.

1.9.3 Benchmarks

Table 11 The default benchmark category boundaries for the biotic index (SASS).

Class boundary	Range of ASPT Scores
Natural	7
Good	6
Fair	5
Poor	<5

1.9.4 Reference conditions

Ideally the invertebrate Reference condition will already have been developed as part of a much wider Ecoregions programme (which is the objective of the River Health Programme). The Reference condition for a particular Level 2 Ecoregion then forms the basis against which the Present state is compared. In the absence of predetermined Reference condition data, it is necessary to provide a method for the establishment of the Reference condition for a site under investigation. This is the purpose of the method below.

If the Reference condition ASPT values, as determined by site survey or as presented in an Ecoregion description, are >5% different to the Natural boundary in Table 11, this indicates that the values in Table 11 need to be adjusted as described below. Adjustment is only permissible as part of a Medium or High confidence Reserve assessment.

Note that the Reference conditions established for a different river in the same Level 2 Ecoregion may be used as the Reference condition for subsequent assessments. Once established for each Level 2 Ecoregion, further investigation into the Reference condition is not necessary.

Adjustment of Table 11

Where local conditions (e.g. naturally anoxic river; acid rivers in the Western Cape) suggest that the Natural condition of a river cannot be assessed against the values in Table 11 the entire table can be adjusted by resetting the boundary of the Natural Class as follows:

- Locate >3 sites that are in a minimally impacted condition and which fit within the broad ecological description of the site under investigation. The ecological description should comprise information that would place the sites into the same Level 2 Ecoregion (Kleynhans & Hill 1999). This will include similar attributes such as altitude, rainfall, geology, habitat and also river size.
- Document the reasons and justify the selection of the sites as minimally impacted sites.
- Collect SASS data from each of these sites on one occasion during a non-high flow season (Medium confidence assessment) or at least three times during the non-high flow seasons (High confidence assessment).
- Use the collected data to establish the median ASPT Score. After subtraction of 5%of this median score, this becomes the boundary of the Natural class.
- The boundaries of the Good and Fair classes are set in bands of 1 ASPT below the Natural boundary. The width of the classes should not be greater than 1 ASPT but with motivation, may be less.
- Where no minimally impacted sites exists within the Level 2 Ecoregion, a constructed Reference Condition may be developed using historical information and expert local

knowledge. Invertebrate families known to have existed at a site may be added to a SASS assessment, and recent invaders removed. Supporting information and justification for doing this must be provided.

Low confidence

- Table 11 should be used as presented and may not be adjusted for local conditions unless pre-existing Reference site data is available from a river within the same Level 2 Ecoregion. Where it is suspected that this table is not appropriate for local conditions, and no pre-existing data is available, then the assessment should be elevated to a Medium Confidence assessment. The reasons for this should be defensible and well documented.

Medium confidence

- The Natural boundary in Table 11 may be used directly provided that some justification is given that this is representative of the relevant Level 2 Ecoregion. Justification can take the form of previous SASS data, expert opinion or the interpretation of historical data.
- Where there is doubt about the Natural boundary in Table 11, the table should be adjusted as described above, by collecting SASS data from three minimally impacted sites within the same Level 2 Ecoregion on one occasion during a non-high flow season.
- The Natural boundary is set as described above.

High confidence

- For a High confidence Reserve assessment, Table 11 is not used as presented, but must be adjusted as described above. SASS data from three minimally impacted sites within the same Level 2 Ecoregion must be collected during three non-high flow seasons.
- In addition to using SASS data to determine the Reference condition, any additional information gained from detailed species data may be incorporated. For example, the presence of rare species or species that are particularly vulnerable to certain impacts, may be included and used to override the SASS boundaries. Where this is done, full justification must be provided.

1.9.5 Present state classification

Low confidence

- Only a single site representing each Resource Unit (determined in the initial part of the Reserve procedure) need be visited on a single occasion. SASS ASPT information is collected from this site.
- The ASPT data is compared with Table 11 (as presented or as adjusted when determining the Reference condition) to determine the Present state.

Medium confidence

- Only a single site representing each Resource Unit need be assessed.
- The site should be surveyed for at least three non-high flow seasons, with at least a single sample per season.
- All data from each Resource Unit should be combined and represented by the median value.
- The ASPT data is compared with Table 11 (as presented or as adjusted when determining the Reference condition) to determine the Present state.

High confidence

- Three or more sites per Resource Unit should be surveyed, covering a maximum spread of the habitat diversity within the Resource Unit. If preliminary surveys show that the data between these sites has narrow variability (< 1 ASPT) then a single site can be used to characterise the Resource Unit for follow-up surveys.
- All three, or the single representative site (discussed above), should then be surveyed for at least three non-high flow seasons, with at least a single sample per season
- All data from each Resource Unit should be combined and represented by the median value.
- The ASPT data is compared with Table 11 (as presented or as adjusted when determining the Reference condition) to determine the Present state.

1.9.6 Ecological specifications

The Ecological specifications are read off the calibrated biotic index benchmark boundary table (or the default biotic index benchmark boundary table (Table 11) if no adjustments were made).

1.9.7 Additional information

No additional information.

1.9.8 References

Chutter, FM (1998) **Research on the rapid biological assessment of water quality impacts in streams and rivers.** Water Research Commission, Report No. 422/1/98, Pretoria, South Africa.

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Kleynhans, CJ & Hill, L (1999) Ecoregional Typing. Resource Directed Measures for Protection of Water Resources: River Ecosystems. Version 1. Department of Water Affairs and Forestry, Pretoria, South Africa.

1.10 CHLOROPHYLL a AS INDICATOR OF ALGAL ABUNDANCE

1.10.1 Rationale

An assessment of only the dissolved nutrient status in a water quality resource unit can lead to an incorrect conclusion about the trophic status of that reach. Dissolved nutrients are directly available for uptake by plants with the result that soluble, inorganic N, P or both may be low during active growth periods when the demand for nutrients are high. In these circumstances, dissolved nutrient concentrations may be a poor predictor of plant biomass in the river (EPA, 2000).

Algae, whether attached to substrates (periphyton) or free floating (phytoplankton) cause most of the problems associated with excessive nutrient enrichment. Algae are directly responsible for excessive, unsightly periphyton mats or surface plankton scums, it may cause high turbidity, and algae are indirectly responsible for diurnal changes in dissolved oxygen and pH.

The phytoplankton and periphyton levels in rivers and streams are affected by geological, physical and biological habitat factors if there is an adequate supply of nutrients (EPA, 2000). Often the system is dominated by phytoplankton or by periphyton (see descriptions below).

Phytoplankton-dominated systems	**Periphyton-dominated systems**
High Phytoplankton Biomass ▪ low current velocity(< 10 cm/s)/long ▪ detention time (>10 days) and ▪ low turbidity/colour and ▪ open canopy and ▪ greater stream depth and ▪ greater depth to width ratio	High Periphyton Biomass ▪ high current velocity (>10 cm/s) and ▪ low turbidity/colour and ▪ open canopy and ▪ shallow stream depth and ▪ minimal scouring and ▪ limited macroinvertebrate grazing and ▪ gravel or larger substrata and ▪ smaller depth to width ratio
Low Phytoplankton Biomass ▪ high current velocity (>10 cm/s)/short detention time (<10 days) and/or ▪ high turbidity/colour and/or ▪ closed canopy and/or ▪ shallow stream depth	Low Periphyton Biomass ▪ low current velocity (< 10 cm/s) and/or ▪ high turbidity/colour and/or ▪ closed canopy and/or ▪ greater stream depth and/or ▪ high scouring and/or ▪ high macroinvertebrate grazing and/or ▪ sand or smaller substrata

A number of indicators can be used to assess the trophic response of a river to nutrient enrichment. These include ash free dry mass, algal cell biovolume, algal species composition, or productivity/respiration ratios. However, chlorophyll *a* concentration is the most widely used indicator of algal biomass in South Africa. Chlorophyll *a* is a photosynthetic pigment found in algae and is a sensitive indicator of algal biomass. It can be considered the most important biological response variable for nutrient-related problems. Benthic chlorophyll *a* can be difficult to measure reliably due to its patchy distribution and occurrence on non-uniform stream bottoms. However, standard sampling methods are available to reduce uncertainty caused by the uneven distribution of periphyton in streams and rivers (Barbour *et al*., 1999; EPA, 2000).

Periphyton is often analysed for AFDM (Ash Free Dry Mass), which includes non-algal organisms. In turbid rivers, AFDM measurements can lead to incorrect conclusions about the periphyton biomass present because a sample may be dominated by sediment deposited in the periphyton mat.

1.10.2 Conditions for using this variable

Optional variable. The chlorophyll *a* response variable is used in those cases where there is evidence that the effects of nutrient enrichment is manifested as high phytoplankton or periphyton biomass, or if observed chlorophyll *a* data are readily available.

1.10.3 Benchmarks

Table 12 The default benchmark category boundaries for Chlorophyll *a* as an indicator of algal abundance

Boundary	Mean annual Phytoplanton* Chlorophyll a (µg/l)	Median Periphyton** Chlorophyll a (mg/m^2)
Natural (Oligotrophic)	<10	< 1.7
Good (Mesotrophic)	10 – 20	1.7 – 21
Fair (Eutrophic)	20 – 30	21 – 84
Poor (Hypertrophic)	>30	> 84

* - Values derived from DWAF (2002), Walmsley & Butty (1980) and Walmsley (1984)
** - Values derived from Biggs (2000:73). These values should be validated for South African river systems.

1.10.4 Reference conditions

The assessment is recommended for low, but required for medium and high confidence assessments. Examine the present state nutrients concentrations. If the nutrient concentrations are relatively low, but there is evidence of high primary productivity, then follow this procedure:

Low confidence

- Use the Natural boundary directly unless there is an indication of significant ecological uniqueness.

Medium confidence

- Refer to Natural boundary in the default benchmark table (Table 12).
- Compare UNIMPACTED data, or derived data, to the benchmark table.
- Use a minimum of 25* samples collected over a 1-3 year period at an unimpacted site, including wet and dry seasons, to calculate the median concentrations. Compare the median values to the default Natural boundary values in Table 12. If the

median value is higher than the default Natural boundary value, then calibrate the default benchmarks as follows:
  - move the default Natural boundary value for phytoplankton and/or periphyton chlorophyll *a* to the value of the median concentration of the reference data. This is the new Natural boundary, and is used to calibrate the Good boundary.
  - For *phytoplankton* chlorophyll *a* move the Good boundary by half the amount by which the Natural boundary was changed, or in other words [Calibrated Good = Default Good + 0.5 x (Calibrated Natural – Default Natural)].
  - For *periphyton* chlorophyll *a* move the Good boundary by two times the amount by which the Natural boundary was changed, or in other words [Calibrated Good = Default Good + 2 x (Calibrated Natural – Default Natural)].
- Calculate the confidence in the data as described in Jooste & Rossouw (2002).
- * - Note that 25 samples is the minimum number of samples required to yield a power statistic of between 0.6 and 0.8 that is regarded as medium confidence.

High confidence

- Refer to Natural boundary in the default benchmark table (Table 12).
- Compare UNIMPACTED data, or derived data, to the benchmark table.
- Use a minimum of 60* samples collected over a 1-3 year period at an unimpacted site, including wet and dry seasons, to calculate the median concentrations. Compare the median values to the default Natural boundary values in Table 12. If the median value is higher than the default Natural boundary value, then calibrate the default benchmarks as follows:
  - move the default Natural boundary value for phytoplankton and/or periphyton chlorophyll *a* to the value of the median concentration of the reference data. This is the new Natural boundary, and is used to calibrate the Good boundary.
  - For *phytoplankton* chlorophyll *a* move the Good boundary by half the amount by which the Natural boundary was changed, or in other words [Calibrated Good = Default Good + 0.5 x (Calibrated Natural – Default Natural)].
  - For *periphyton* chlorophyll *a* move the Good boundary by two times the amount by which the Natural boundary was changed, or in other words [Calibrated Good = Default Good + 2 x (Calibrated Natural – Default Natural)].
- Calculate the confidence in the data as described in Jooste & Rossouw (2002).
- * - Note that 60 samples is the minimum number of samples required to yield a power statistic of greater than 0.8 that is regarded as high confidence.

1.10.5 Present state classification

No chlorophyll *a* data are available

- For a low to medium confidence assessment - Use visual observations made during a site visit(s) to record a qualitative, expert judgement of the present algal abundance status. Provide adequate reasons for the assessment and rate the confidence as low.
- For a high confidence assessment: during the visit to the site, use available information and expert judgment to decide whether the site is phytoplankton or periphyton dominated. Use standard sampling methods to collect phytoplankton or periphyton samples and analyse these for chlorophyll *a*. Use the measured chlorophyll *a* concentration and default chlorophyll a benchmarks to classify the present algal abundance state. The confidence for this assessment will be low because it is based on a few samples collected during the site visit.

If chlorophyll *a* data are available

- Assemble the Chlorophyll *a* from the most recent 5 years of the data record.
- Calculate the average of the phytoplankton chlorophyll *a* or the median of the periphyton chlorophyll *a*.
- Compare the mean or median concentrations to the default chlorophyll *a* benchmark table (Table 12), or the calibrated chlorophyll benchmark table that was modified using reference data, and classify the present chlorophyll status.
- Calculate the confidence in the chlorophyll data set as described in Jooste & Rossouw (2002) and, using the power statistic, express the confidence as low ($p<0.6$), medium ($0.6>p<0.8$) or high ($p>0.8$).
- Provide a qualitative statement expressing your confidence in the data set to represent the spatial and temporal algal abundance status of the whole resource unit.

1.10.6 Ecological specifications

The Ecological specifications are read off the calibrated chlorophyll benchmark boundary table (or the default chlorophyll benchmark boundary table if no adjustments were made).

1.10.7 Additional information

Sampling and analysis methods

Phytoplankton:
Standard methods for collecting water samples for phytoplankton analysis can be found in DWAF (2002) or van Ginkel (2001). Standard methods for the extraction and analysis of chlorophyll *a* from the samples are given in APHA (2000) or DWAF (1992).

Periphyton:
Standard methods for the sampling of periphyton for chlorophyll (and biomass) analysis are given in EPA (2000), Barbour *et al*., (1999) and Biggs & Kilroy (2000). Standard methods for the extraction and analysis of chlorophyll *a* from the samples are given in APHA (2000) or DWAF (1992).

1.10.8 References

APHA (2000) **Standard Methods for the Examination of Water and Wastewater.** Twenty first edition. Eaton, A.D., Clesceri, L.C. and Greenberg, A.E. (eds.). American Public Health Association, Washington, DC.

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Walmsley, RD & Butty, M (1980) **Guidelines for the Control of Eutrophication in South Africa.** Water Research Commission, National Institute for Water Research, CSIR, Pretoria, South Africa.

Walmsley, RD (1984) A Chlorophyll a trophic status classification system in South Africa. Water Research Commission, Special Report., Pretoria, South Africa.

1.11 TOXICITY

1.11.1 Rationale

While it is recognised that toxicity tests are an important biological response variable, their inclusion in the Reserve assessment procedure is not yet fully understood. Methods for incorporating toxicity tests in the Reserve procedure are under development.

2. PRESENTATION OPTIONS FOR INFORMATION REQUIRED FOR AN ECOLOGICAL WATER REQUIREMENTS (RIVERS) ASSESSMENT FOR WATER QUALITY

2.1 PRESENTATION OPTIONS

In this section, examples are given of options to present the:

- Data and information used,
- Reference and present state concentrations, and
- Ecological specifications for water quality resource units.

2.1.1 Data and information used

The RDM reporting format requires a brief summary of the data sources used to derive the reference and present state categoryes. The table can be accompanied with a short description of the water quality resource unit describing features that affect the quality in the resource unit. These features include a brief description of the dominant land-use, important point or non-point sources, important tributaries and their impact on the quality in the resource unit and any other features that should be noted. Where data was extrapolated from adjacent catchments, proper motivation should be provided.

Example of a summary table of the data sources

Explanation	**Reference state site**	
Name & number of the reference state site	Monitoring station	H2H015Q01 – Roode Els Berg Dam: downstream weir
Length & number of observation in the full data record & in data record used	Data record	Full data record - 1977 – 2001 (222 data records) Data record used – 1996 – 2001 (57 data records)
Overall trend increasing, decreasing or stable	Trend significance	Slight decreasing trend
List of known point sources or significant non-point sources upstream of the site	Known point sources upstream	None
Confidence in the data set to characterise background reference conditions for the resource unit	Confidence	High
	Present state data	
Name & number of the present state site	Monitoring station	H2H006Q01 – Hex River at Glen Heatlie
Length & number of observations in the full data record & in data record used	Data record	Full data record - 1980 – 2001 (965 data records) Data record used – 1997 – 2001 (144 data records)
Overall trend increasing, decreasing or stable	Trend significance	Overall trend is stable. No overall trajectory of change detected but TDS shows cyclical changes, TDS increase during wet years & decrease during dry years.

List of known point sources or significant non-point sources upstream of the site	Known point sources upstream	None, only agricultural non-point sources in the Upper Hex River
Confidence in the data set to characterise the present state of the resource unit.	Confidence	High

2.1.2 Reference and present state concentrations

The reference and present state categoryes can be summarized in a table. It is important to document any deviations from the recommended methodology and to provide a motivation for the deviation.

An example of a reference or present state summary table.

Variable group	Variable	Value	Category	Comment
Inorganic salts (95th percentile)	Na_2SO_4 (mg/l)	10.84	Natural	H2H015Q01 data
	$MgCl_2$ (mg/l)	9.48	Natural	H2H015Q01 data
	$CaCl_2$ (mg/l)	9.81	Natural	H2H015Q01 data
	KCl (mg/l)	1.65	Natural	H2H015Q01 data
	$MgSO_4$ (mg/l)	0	Natural	H2H015Q01 data
	$CaSO_4$ (mg/l)	0	Natural	H2H015Q01 data
	NaCl (mg/l)	7.30	Natural	H2H015Q01 data
Nutrients (50th percentile)	PO_4-P (mg/l)	0.014	Good	H2H015Q01 data
	TIN (mg/l)	0.040	Good	H2H015Q01 data
Physical variables	Temperature (°C)	No observed data record		Concern about the effect of the Roode Els Berg Dam on water temperatures in the lower Sanddrifkloof River.
	Dissolved oxygen (mg/l)	No observed data record		No concerns noted about low DO stress on organisms.
	Turbidity	No observed data record		Temporary increase observed in turbidity during rainfall runoff events
	pH (range)	6.6-6.9	Natural	H2H015Q01 data
Response variables	Biotic community composition (ASPT score)	8.57	Natural	All biotopes (refer to invertebrate report)
	Algal abundance	No data		Visual observations - substrate free of periphyton
	Toxicity	No data		No concerns noted

2.1.3 Ecological specifications

The eco-specs can be summarised in a table where any deviation from the default boundary values should be noted. The present state for each variable can also be noted by shading the appropriate cells. This will guide the Department when a decision has to be made about the future management class and the eco-specs for the resource unit under consideration.

An example of presenting ecospecs in a table format

Variable group	Variable	Natural	Good	Fair	Comment
Inorganic salts (95th percentile)	Na_2SO_4 (mg/l)	12	48	84	
	$MgCl_2$ (mg/l)	9	37	64	
	$CaCl_2$ (mg/l)	17	85	152	
	KCl (mg/l)	88	107	125	
	$MgSO_4$ (mg/l)	59	165	271	
	$CaSO_4$ (mg/l)	21	495	968	
	NaCl (mg/l)	3	602	1200	
Nutrients	PO_4-P (mg/l)	0.005	0.025	0.0125	
	TIN (mg/l)	0.25	1	4	
Physical variables	Temperature (°C)				Not assessed
	Dissolved oxygen (mg/l)		6	4	Not assessed
	Turbidity				Not specified
	PH	5.5-6.5	6.0-7.5	6.5-8.0	Natural boundary adjusted for Western-Cape mountain stream conditions
Response variables	Biotic community composition (ASPT score)	7	6	5	
	Algal abundance (Periphyton Chl *a* µg/l)	3	25	260	Not assessed
	Toxicity	*Natural – 100% species protection extrapolated from 95% CEV* Good – 95% species protection based on 95% CEV Fair – 100% species protection extrapolated from 95% AEV			Not assessed

Note: Shaded cells indicate the present state

Temperature ecospecs

Temperature ecospecs are specified as monthly values indicating the upper and lower boundaries of natural, good and fair categories.

An example of specifying temperature ecospecs in a table format

Calendar month	1	2	3	4	5	6	7	8	9	10	11	12
Upper Fair	30	28	26	24	20.4	16.8	14.4	15.6	19.2	20.4	24	26.25
Upper Good	28	26	24	22	18.7	15.4	13.2	14.3	17.6	18.7	22	24.25
Upper natural	26	24	22	20	17	14	12	13	16	17	20	22.25
Lower natural	22	20	19	16	14	10	11	11.5	12	13	13	16.5
Lower good	20	18	17.1	14.4	12.6	9	9.9	10.35	10.8	11.7	11.7	14.85
Lower fair	18	16	15.2	12.8	11.2	8	8.8	9.2	9.6	10.4	10.4	13.2

Note: the shaded cells indicate the poorest category of the present state.