HYDROLOGICAL INFORMATION AND TECHNIQUES TO SUPPORT THE DETERMINATION OF THE WATER QUANTITY COMPONENT OF THE ECOLOGICAL RESERVE FOR RIVERS

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Table of Contents **Page**

LIST OF TABLES Page

LIST OF FIGURES **Page**

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ABBREVIATIONS

BBM	Building block methodology
BFI	Baseflow index (proportion of total streamflow that equals baseflow)
DWAF	The Department of Water Affairs and Forestry
EMC	Ecological management class
HYMAS	Hydrological modelling application system
IFR	Instream flow requirement
IWR	Institute for Water Research
MAR	Mean annual runoff
VTI	Variable time interval model
WR90	Surface Water Resources of South Africa, 1990

EXECUTIVE SUMMARY

The original proposal for this project referred to promoting the more widespread use of observed or simulated daily streamflow data in various fields of water resource decision-making and management. One of the areas that was to be addressed was the determination and implementation of instream flow requirements (IFRs), which the hydrology section of the Institute for Water Research had started to get involved with during 1995. The perception was that there was a great deal of room for improvement in the manner in which the hydrological component of IFR studies was dealt with. The improvements that were considered fall into four basic categories :

❑ The preparation of daily time series of natural and present day streamflows.
❑ The presentation and use of this information by the non-hydrological specialists at the IFR workshops.
❑ The interface between the results being generated by the workshop participants and the water resource planning engineers who are required to incorporate the IFR into their designs.
❑ The translation of the tools used for planning and design into additional tools that can be used for real-time management.

The first point has been addressed mainly by Dr Vladimir Smakhtin (who has subsequently left the Institute) who is the author of a separate report (WRC Report No. 867/1/2000) associated with this project and which deals with pragmatic approaches to estimating daily flow time series in data sparse areas. The second point has also been addressed through the second report on this project (WRC Report No. 867/2/2000) that outlines the development of software to display and analyse time series data. The intention of this component of the project was to develop tools for presenting the hydrological time series data to non-hydrological specialists in an informative, flexible and interactive manner. The software is still under development, but a prototype version has been available for some time and has been used in several IFR workshops, as well as being transferred to other university departments where there are research groups working on related problems. It is believed that, although many improvements can be made to the functionality of the software, it has proved to be useful and has facilitated the transfer of hydrological understanding to other specialists involved in IFR workshops.

While this report, therefore, focuses on the final two points, the research that was originally planned has been overtaken by other developments in the approaches used to plan and manage South African water resources - specifically the New Water Act and the concept of the Ecological Reserve.

Prior to the new Water Act, a limited number of IFR determinations were required and they were mostly carried out for quite large proposed water resource development schemes. The substantial resources required to collect and process the relevant information (on ecology, hydrology, hydraulics, geomorphology and social issues) could, therefore, be reasonably well justified. However, the need to determine (even at a relatively low level of confidence) the reserve requirements for all significant water resources in the country in a relatively short period of time suggested that the methods that had been used for the IFR workshops of the past would only be appropriate for those sensitive situations where a high level of accuracy and confidence could be justified. A further set of tools was required to enable the reserve to be quantified as preliminary, or initial, estimates with far fewer resources (and therefore cost) than would be used normally. From a hydrological point of view this meant that the use of daily streamflow time series became inappropriate, as they are not readily available at a sufficient number of locations countrywide.

The Surface Water Resources of South Africa 1990 volumes (WR90) and databases provide 70 year monthly time series of naturalised flows for all 1946 quaternary catchments of the country (including Swaziland and Lesotho) and these were then considered appropriate to use as the base data for any new techniques. In moving towards methods that were to be based on monthly time series (rather than daily), it was believed by many of the specialists involved suggested that the best approach would be to try and preserve as much of the conceptual basis of the existing methods (essentially the BBM - Building Block Methodology) as possible. It was also recognised that this would never be a simple task, given that the BBM is based on a great deal of expert judgement and quite detailed links between habitat, hydraulics and hydrology - links that are reasonably possible using daily streamflow data, but not easy using monthly data. One of the major reasons for wishing to preserve the conceptual base was that developments at one end of the scale could lead to further improvements at the other end without having to completely redesign the links between them. It also makes it easier to develop a continuum of methods from the high confidence, detailed approaches to the low confidence, low-cost and simple approaches.

This report summarises the hydrological information requirements of the various levels of ecological reserve determination for the water quantity component in rivers (it does not address water quality issues, nor explicitly the Reserve for groundwater bodies, estuaries or wetlands) in section 2. For the purpose of the report and the hydrological data inputs, reserve determinations have been divided up into 5 phases: data generation, data interpretation, design flow requirements, scenario planning and implementation. The options and methods available for satisfying the hydrological information requirements at various levels are discussed, from the low-confidence (and cost) Desktop approach to the much higher confidence (and cost) Comprehensive Reserve. This section does not provide a great deal of detail about the approaches as they have been more fully documented elsewhere or are covered in greater depth in other sections of the report. The summary does, however, provide an indication that the project has been able to put into place tools which are appropriate to the problem, even if they are not perfect at this stage. In that respect, the project has been successful and a sound basis for future developments has been laid. Some problems were only identified during the project and the project team had to respond quite rapidly to emerging concepts. It was never anticipated that final answers would be achievable within the short time that was available.

The third section of this report addresses the Desktop and Rapid estimation procedures in more detail as these were developed (from start to their current level) wholly during this project. There was a great deal of interaction between the project team, various members of the IFR specialist community, various sections of DWAF and consulting water resource engineers before the concepts could be developed to their current level. This was, therefore, a truly multi-disciplinary effort that combined not only a number of disciplines, but also research staff together with private and government practitioners. The Desktop approach is almost completely based upon the hydrological characteristics of rivers and the biotic component is only included through a series of fairly subjective parameters. These have been based on extrapolations from previous detailed IFR studies and some more recent inputs of expert judgement. The reason for this is that the hydrological data are available (through WR90) nationwide, while quantitative information on the biotic components is not. The final result is a pragmatic, but nevertheless, far from satisfactory approach which leads to the 'low confidence' label that is given to the results. The Desktop approach is now being used within the National Water Balance Model to populate the database with rough estimates of the reserve requirements (for water quantity in rivers) at the outlet of every quaternary catchment for the full range of Ecological Management Classes (EMC). Section three describes the basis and use of the software that has been written to carry out these calculations, as well as noting some of the assumptions that have been made.

Section three also describes a more site-specific application of the Desktop approach which can be used with WR90-type data files, or alternative simulations/observations of monthly data which are stored in a similar format. In this computer program, the user has far greater flexibility in being able to over-ride or adjust the default generic regional parameter values. This program is, therefore, equally applicable to the Rapid Reserve approach, where there is scope for limited input of some site-specific ecological expertise, which may determine the most appropriate EMC to be used or which may be able to identify the range of flows that might be expected during different seasons of the year. The software has built-in procedures for visualising the input data and parameters, modifying them where necessary and assessing the results. The software package has been distributed to various groups for use (specifically DWAF) and evaluation (other University groups) and a version of section three has been posted on the IWR web site at Rhodes University so that updates can be communicated efficiently to existing and potential users.

Section four is the result of a short-term additional programme that was established during the final year of the project to assess the potential of including more ecological information in the Desktop and Rapid Reserve methods. The sub-project was an attempt to identify generic riverine habitat characteristics that could be used to differentiate between rivers with similar hydrological regime characteristics. A typical question to be asked was '*can it be said that sand bed rivers would have lower instream flow requirements than cobble bed rivers*'? The project was based upon canvassing a number of experts in the field of IFR, integrating their responses and trying to approximately quantify their opinions to develop an initial scoring system. The section outlines the results of the work, provides some insights into the problems experienced and summarises the very tentative initial scoring system that was developed. This system is not to be viewed as final, but is more of an example of the type of approach that could be adopted to improve the Desktop and Rapid methods. It needs to be refined by the same specialists who were consulted to develop it.

Section five returns to the use of daily streamflow data and reports on the current developments of a prototype program for dealing with IFR and Reserve requirements in real-time. This software is being developed as a contribution to the implementation of IFRs on the Sabie/Sand system in Mpumalanga and represents a real time application of the low-flow component of a model that was developed in 1996 (Hughes et al., 1997) to link BBM workshop results to the data requirements of the water resource yield modellers in a way that was transparent to the ecological specialists. While some of the problems of real-time operation still exist, the software that has been developed represents a step in the right direction.

The project team believe that advances have been made over the last few years in the use of hydrological data within the BBM and Reserve processes. However, there are still many areas where further developments can be made to improve the use of the data and to make the use of the data clearer to other specialists. This executive summary concludes with a few points that can be considered to be ‘recommendations for further work and actions’ :

- ❏ The incorporation of more explicit ecological and geomorphological information into the simple estimation procedures and the development of more objective and consistent approaches to the relationships between hydrology and ecological functioning.

- ❏ The integration of a range of existing and new methods that contribute to setting the reserve into a single computer package that makes them more accessible to existing and new users.

- ❏ The addition of Decision Support Guidelines into the computer package referred to above to facilitate the use of the software by new users.

- ❏ The training of more users in the approaches and software developed for applying hydrological information within reserve determinations. There are relatively few specialists in this area and yet there appears to be the potential for quite a substantial amount of work.

1. INTRODUCTION

This report forms one of three parts of the final report on the project **'Integration and application of daily flow analysis and simulation approaches within southern Africa'**. The other two reports address different components of the project, but they are all linked. One section of this report also includes a section that addresses a short-term project carried out by the IWR for the WRC on an investigation into the inclusion of physical and biological factors into otherwise hydrological-based methods for rapid, low-confidence estimates of the ecological flow rquirements of rivers.

The second report (Smakhtin, 2000) describes some of the research that has concentrated on pragmatic methods of generating daily time series of flows for South African catchments using readily available data. These methods are being used more frequently in place of more data-intensive approaches that are often inappropriate, given the time, finance and data resource constraints associated with some of the reserve determination methodologies. The second report (Hughes, et al., 2000) describes the development of a software package for the analysis and display of hydrological and water resources time series data, which has been already used extensively during a number of instream flow requirement workshops and reserve determinations.

Prior to the start of this project in 1997, the Institute for Water Research had been involved in several IFR workshops and had begun to develop methods to support this process. Some of these methods related to the preparation of the hydrological data required by the other IFR specialists (ecologists, riparian vegetation specialists, freshwater ichthyologists, geomorphologists, hydraulic specialists, etc.) and some to methods related to processing the workshop results into a format suitable for use by the water resource engineers responsible for system designs. This report concentrates on the work that has been carried out during the current project (1997 to 1999), but will also make extensive reference to previous developments. Many of these previous developments are summarised in the hydrology section of the report edited by King (2000) or discussed in various papers published in Water SA (Hughes, et al., 1997, Hughes and Ziervogel, 1998 and Hughes, 1999).

DWAF is now in the process of implementing the new legislation relating to the control and licensing of water abstractions from all significant water bodies within the country. Part of this legislation(DWAF, 1997), refers to the need to ensure that the requirements for both basic human needs and the environment are met before potential users can be licensed to abstract water. These two requirements are referred to as the '*Basic Human Needs Reserve*' and the '*Ecological Reserve'*. Quantifying the Ecological Reserve is about determining the water quantity and quality requirements of rivers, estuaries, wetlands and aquifers in order to ensure that they are sustained in a pre-determined condition. This pre-determined condition is referred to as the EMC and is related to the extent to which the required condition differs from natural or pristine conditions. There are four main classes (A to D), where A refers to a condition that is largely natural, while D assumes a largely modified condition where there is a large loss of natural habitat, biota and basic ecosystem functioning. The responsibility of determining which class should be used for a specific water body lies with the Minister of Water Affairs and Forestry after consultation with stakeholders. The reserve has, therefore, superceded all other water resource management requirements in terms of setting instream flow requirements and has introduced a new element of urgency with respect to the need to quantify ecological flow requirements for many rivers of South Africa.

This report is divided up into three main sections. The first presents a summary of the hydrological information requirements for determining the Reserve and reviews some of the possible approaches to satisfying those requirements. The second explains the detail of the desktop estimation methods that have been developed during the course of this project, while the third discusses the potential for including physical and biological factors into some of the more rapid Reserve determination methods.

2. HYDROLOGICAL INFORMATION REQUIREMENTS FOR THE DETERMINATION OF THE ECOLOGICAL RESERVE FOR RIVERS

2.1 Detailed procedures for setting the Reserve

Prior to the new legislation, the IFRs of rivers, subject to existing or future planned water resource developments, were established in South Africa through the BBM process (King and Louw, 1998). The approach made use of specialist input (from ecological experts on fish, invertebrates, riparian vegetation, etc.; geomorphological experts; hydraulic experts and hydrological experts) during a workshop to define the main building blocks that will describe the monthly distribution characteristics of the modified flow regime. While the methodology is being constantly refined and developed, the essential components of flow (the 'blocks') are seen as the low or base flows, the small increases in flow, referred to as freshes, and the larger high flow events that might be required for various channel maintenance purposes. As South African natural flow regimes have long been recognised as being highly variable, the BBM process defines a set of blocks that can be considered to apply during 'normal' years (referred to as the 'maintenance' requirements), as well as a set that should be applied during drought years ('drought' requirements). While these definitions of when the different blocks are expected to occur are quite vague, it has always been recognised that natural climatic cues should determine their timing and frequency of occurrence. The final set of building blocks consists of the following for each month of the year :

Maintenance low flows expressed in $m^3 s^{-1}$
Maintenance high flow events defined as peak flows in $m^3 s^{-1}$ and durations in days
Drought low flows expressed in $m^3 s^{-1}$
Drought high flow events defined as peak flows in $m^3 s^{-1}$ and durations in days

Each of the requirements is associated with a justification based on one or more of the specialist fields. The hydrological specialist is required to provide the background data on the natural and present day flow regimes in as much detail as possible. The ecological and geomorphological requirements, in terms of flow depths, widths and velocity, can then be checked against the rivers flow 'experience' after being converted to flow rates using the available hydraulic data.

There are five reasonably well defined steps in the whole IFR process from the point of view of the hydrological information and analysis tools that have to be provided : *The Data Generation phase* is designed to generate representative time series of natural and present day flow regime conditions and is the main task carried out by the hydrological specialist prior to the workshop. *The Data Interpretation phase* is the main task of the hydrological specialist during the workshop and involves the use of the generated time series to assist the other specialists in making decisions about the ecological flow requirements and ensuring that they do not set flows which are unrealistic from the point of view of what would be expected to occur in the river under natural conditions. *The Design Flow Requirement phase* involves transfer of the workshop results to a water resource systems analysist so that the impacts of satisfying the ecological reserve requirements on the water supply yield of the catchment can be evaluated. In order to achieve this, information must be provided about when maintenance (or above) flows are required and when drought flows are required. This step is, therefore, mainly about defining the levels of assurance with which the various building blocks are required to be met. *The Scenario Planning phase* is designed to resolve any disparities between the IFR and the required yield and could involve reassessment of the workshop results, redefinition of the IFR assurance rules, a change in management class or a redesign of the water supply engineering scheme. *The Implementation phase,* involves designing the procedures that will be followed to implement the scheme and to ensure that the final reserve will be met.

2.1.1 Data generation phase

It is rare for IFR sites to be close to existing flow measurement sites and some form of hydrological modelling is necessary to be able to generate representative daily flow time series. Even where the IFR sites are close to a gauging weir, the historical flow records are often impacted by upstream land-use or water abstraction developments, particularly during the recent past. A further consideration is that the amount of time allocated to the preparation of the hydrological data is very limited (as little as 6 days for a relatively large river system with about 5 IFR sites). Two main approaches have been used by the IWR: a daily time step, semi-distributed, rainfall-runoff model (VTI model - Hughes and Sami, 1994) and a daily time step spatial interpolation model based on flow duration curves (Patching model - Hughes and Smakhtin, 1996). These are the only two models referred to in this paper because they are the most appropriate approaches to use that are also part of the model application system developed at Rhodes University (HYMAS - Hughes et al., 1994). There are many other modelling approaches that could be used and individuals would be expected to select an approach that they were most familiar with.

A daily rainfall-runoff model may be the ideal approach, but the disadvantage is that it requires far greater resources of time and data to achieve a satisfactory result. Such models are only usually appropriate if adequate observed streamflow data are available for calibration and validation, and if the user's knowledge of both the catchment's hydrological response and the model's structure allows a solution to be achieved within the available time. The model should normally be capable of simulating historical changes in artificial influences on the flow regime (caused by dynamic patterns of abstractions and land-use change) so that a calibration against observed streamflows can be achieved. A representation of the natural regime can then be simulated by removing the artificial influences (through appropriate parameter value modifications), while the present day regime can be represented by a simulation based on fixed current artificial influences. Some of the problems experienced in South Africa relate to the influence of poorly defined artificial upstream influences, while others relate to gauge accuracy and the inability of many South African flow gauges to measure flows above certain thresholds. Most of the data problems are common to any simulation approach and the issue then becomes one of comparing the amount of time spent on the modelling study with the expected confidence in the results.

The Patching model (Hughes and Smakhtin, 1996) has been used quite frequently, not because it can generate better results, but because the expected confidence in the results of applying a rainfall-runoff model would be so low that a simpler technique becomes appropriate. The principle of the model is that the duration curve percentage point for a specific flow at a defined 'source' site is first quantified and then translated into a flow value at a 'destination' site using the same % point on the destination site's duration curve. The model, therefore, requires that duration curves are available for the 'destination' site. In the context of this paper, 'destination' sites refers to IFR estimates that are made and source sites would be gauged as streamflow sites. Several source sites can be used with differential weightings for each destination site.

Application of the model for an IFR workshop involves selecting several observed flow gauges and developing regional, non-dimensional, calendar month 1-day flow duration curves (Smakhtin at al., 1997) to represent natural conditions. It may be necessary to apply corrections to parts of some of the duration curves, where upstream flow modifications have been known to occur and can be quantified. This has been found to be possible where the influences are confined to land use changes (afforestation, for example), or to run-of-river abstractions, but is normally impractical for sites below major impoundments. The selection of the flow gauging sites and the parts of their time series to use in developing the regional flow duration curves is an important component of the modelling process. As the regional curves are expressed in non-dimensional flow units (flow/average daily flow, for example) they can be scaled by an estimate of the average daily flow at the IFR site and used as destination curves with the Patching model. Estimates of average daily flow are available from the WR90 volumes (Midgley et al, 1994) which provide MAR values for 1946 quaternary catchments covering the whole of South Africa, Swaziland and Lesotho. Alternatively, a monthly rainfall-runoff model could be calibrated and applied to the site of interest to determine an estimate. Monthly models are commonly much quicker and easier to apply than daily models and regional parameter estimates for the Pitman model (Pitman, 1973) are available from WR90.

2.1.2 Data interpretation phase

Apart from some limited analyses and production of summary graphs and tables for the pre-workshop documentation, the main part of the interpretation phase occurs during the workshop in response to queries from the other specialists. It is, therefore, necessary for the hydrologist to have access to a wide range of time series analysis and display tools to allow questions to be answered and illustrated rapidly and unequivocally. Experience suggests that the following tools are required as a minimum :

☐ Time series display tools that allow daily data to be plotted graphically and scaled in different ways. The tools should allow several time series to be superimposed so that comparisons can be made between sites of interest, between natural and present day conditions or between observed and simulated conditions. It is also useful to have facilities for displaying several years from the same months or seasons on one set of axes so that comparisons can be made between similarly dry (or wet) years to determine typical or extreme response characteristics.

☐ Duration curve generation and plotting tools. These should allow duration curves to be constructed for all or part of a time series, including curves for individual calendar months. The ability to overlay curves from different sites, or for different groups of years within the same time series can also be very useful.

☐ Baseflow separation tools. It is important to have a facility to separate the baseflow streamflow response from the more rapidly responding high flows, given the methods used in the BBM and the need to define low- and high-flow requirements separately. However, it is also necessary to ensure that all the specialists have a common perception of what a separated baseflow represents and how it is to be interpreted. (for example see Nathan and McMahon, 1990).

☐ High- and low-flow frequency analysis tools. These can be of particular value for the Geomorphology specialist in trying to determine the peaks of high flow events that are required for channel maintenance.

However, it should be noted that it is very difficult to ensure accuracy in the estimation of extreme high-flow events given the resolution of the modelling methods commonly used for IFR workshops. This is compounded by the fact that many South African gauges under-estimate flood peaks and that the time series data used are mean daily flows, which under-represent instantaneous peaks in all but very large catchments.

The majority of these procedures form part of the HYMAS package which is a DOS-based suite of time series data preparation, modelling and data analysis programs (Hughes et al., 1994). Many of the models contained within HYMAS, as well as the time series data analysis and display procedures are currently being re-written for a Windows environment using DELPHI (Hughes, 1997).

2.1.3 Design flow requirement stage

This is the phase during which the flow magnitudes specified for maintenance and drought conditions are built up into design requirements in preparation for the scenario planning and implementation phases. Hughes (1999) explains why the table of monthly building blocks are not sufficient for incorporating into the type of water resource systems models that are used in South Africa for planning and design purposes. The main deficiency is that, while the structure and definition of the building blocks imply variations in required flows over time, they do not provide information on the frequency of occurrence or assurance levels of the different flows.

Hughes et al.,(1997) developed the IFR model to address this issue by making use of a reference time series of daily flows to provide climatic cues and a set of rules coupled to the building block values, that allow the cues to be interpreted into actual flow requirements on a daily basis. The reference flow time series can be either observed or simulated data, at the site of interest or at a different site even in an adjacent river. The main consideration is that it reflects the climatic cues occurring in the catchment above the site of interest and has a rainfall-runoff response to these cues that is similar to that which would occur in the river at the site of interest. Problems related to catchment scale and variations in the relative magnitudes of low and high flows, even between closely adjacent catchments, are avoided by dealing with flow duration curve % point equivalents instead of actual flow values.

The details of the model are not repeated here, but the basis of the approach for the low flows is to establish a set of monthly rules for both maintenance and drought requirements, which can then be compared to a smoothed time series of the % point equivalents on a daily basis. If the time series suggests a lower flow (greater % exceedance) than the drought rule, the drought flow is required in the design flow time series. If the time series suggests a flow between the maintenance and drought rules, linear interpolation is used to establish a required flow that lies somewhere between the two flows. If the time series suggests a flow greater than the maintenance rule, a further rule is used to allow the design flow to exceed the maintenance flow by a maximum specified degree. A similar approach is used for the high flow part of the requirements, but is further complicated by the need to have to recognise the occurrence and relative magnitude of events within the reference time series in order to ensure that the design high flows are cued appropriately. The final result of the model is a representative time series of flows that are required to maintain the river in a condition consistent with the EMC specified, which are effectively ‘calibrated’ by the participants. These are the ‘design’ ecological flow requirements and the resulting time series can be summarised in various ways to extract the type of information that the water resource system modellers would require.

2.1.4 Scenario planning phase

During the scenario planning phase, water resource systems models (Basson et al., 1994) are set up to simulate the operation of the system with all possible combinations of storages (reservoirs), demands (for agriculture, industry and domestic) and reserves together with their required levels of assurance of supply, until an optimal yield solution is found. A relatively simple alternative (the DAMIFR model) was developed by Hughes and Ziervogal (1998) and represents a single reservoir water balance simulation where the downstream flow requirements are specified as a time series using output from the IFR model (Hughes, et al., 1997). The model contains a relatively simple procedure for establishing operating rules that can prioritise abstractions and downstream releases in different ways to achieve an optimal yield/IFR requirement solution. What constitutes an optimal solution may vary between projects, depending upon various constraints and priorities. From the point of view of the hydrological specialist, the scenario planning phase may involve repeated runs of the IFR model, in consultation with some of the ecological specialists, to find alternative design ecological flow requirements that will increase the yield of the system, but can be still considered to maintain the ecological management objectives. Unfortunately, this is still a somewhat subjective task, largely due to the complexity of the relationships between the flow regime of a river and its ecological functioning and our lack of detailed understanding of the mechanisms of those relationships.

2.1.5 Implementation phase

The techniques required for this phase are the least well-developed, largely due to the fact that no IFR recommendations have been implemented to date. However, the IFR model (Hughes et al., 1997) was developed with implementation in mind and, therefore, most of the hydrological issues should be able to be readily resolved. The IFR model has also been built into a prototype implementation computer program that allows real time reference flow data to be added to a database and real time estimates of the IFR requirements to be made (see section 5 of this report). One problem that still remains is the question of cueing high flow events, so that any artificial releases coincide with naturally occurring tributary flows downstream. The reason for this requirement is to maximise the 'value' of a high-flow release and not to end up with a larger number of smaller events (some natural and some artificially released) than was designed to occur. The implication is that some form of forecasting would be required, a problem that may be difficult to solve in catchments which have quite rapid response times to rainfall.

A further problem is related to the hydraulics of the channel system and the need to estimate how much water to release from an upstream reservoir (or the extent to which direct abstractions should be limited) to achieve a specified flow some distance downstream. This problem applies to both low- and high-flow requirements, but should be able to be resolved with any one of several hydraulic models that are available internationally. One of the more difficult components of such models to quantify for South African rivers might be channel transmission losses caused by evapotranspiration by riparian vegetation or seepage into underlying aquifers.

2.2 The need for more rapid approaches

It has become clear that the resource intensive methods of applying the BBM are not always appropriate and that quicker methods are required. However, it is still necessary to make use of the ecological expertise to ensure that the results have as high a level of scientific credibility as possible if they are to be used to set the reserve and limit the availability of water for other users. A current project of DWAF, the National Water Balance Model, is designed to assess the present day use and future availability of water resources throughout the country at a relatively coarse spatial scale (quaternary catchments), taking into account natural flows, current reservoir developments, run-of-river abstractions, return flows and land use modifications, as well as the ecological reserve requirements. Initial reserve estimations are required for all quaternary catchments (a total of 1946) in the very near future, a task that would be impossible using the detailed approaches that are part of the BBM.

Four levels of reserve determination are now recognised by DWAF (figure 2.1) : *Desktop estimate*, based on generic, regionalised values, used within the National Water Balance Model and taking no more than a matter of hours to complete. *Rapid determination*, an enhancement of the desktop estimate using limited input from ecological specialists to improve the site-specific application of the generic estimates. This is expected to take no more than about 2 days. *Intermediate determination*, being a 'stripped down' version of the BBM (or similar) approach and taking about 2 months to complete. *Comprehensive determination,* taking as much as 12 months or more to complete and being the detailed application of the BBM (or similar).

One of the issues surrounding the recognition of different levels of determination is that they are quantified with different levels of confidence, from quite low for the desktop method to the highest possible for the comprehensive method. It is also the contention of the author that they should be based on the same general principles. The reason for this is that as more intermediate and comprehensive determinations are carried out, the results can be used to improve the generic, regionalised values that form part of the desktop approach. From a hydrological point of view, the information required by the intermediate approach is essentially similar to that needed for the comprehensive determination, the difference being the reduced time available to carry out the data-generation phase. This emphasises the need for highly pragmatic approaches to the generation of time series of natural daily flows, because setting up and calibrating a daily rainfall-runoff model is no longer an option.

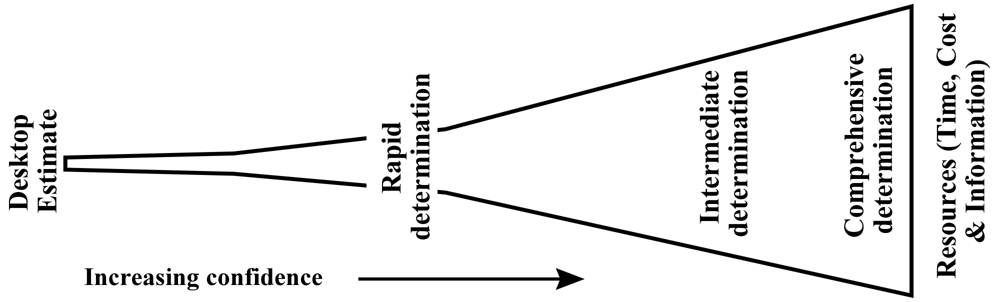


Figure 2.1 Illustration of the relative resources required for the different levels of reserve determination. The width of the 'slice' could also be interpreted as the level of confidence that can be expressed in the results.

2.3 Desktop approach using hydrological extrapolations of past results

While the details of this approach are explained more fully in the next section, a summary is provided here so that the links with the more detailed approaches can be made. The basic principle is that the modified flow regime designed to fulfill the requirements of the reserve should reflect the natural flow regime and Richter at al. (1997) emphasised the fact that hydrological variation is a primary driving force within riverine ecosystems. Discussions held during several IFR workshops suggested further that those rivers within South Africa that have highly variable flow regimes would require a smaller proportion of their mean annual flows to satisfy the reserve than those with less variable regimes. The variability of the flow regimes of South African rivers can be largely explained by a combination of the proportion of their total flow that occurs as baseflow (which provides a measure of the intra-annual, or medium term variability), as well as the longer-term variability and susceptibility to the occurrence of droughts, as reflected in monthly or annual coefficients of variability (CVs). A preliminary analysis using an index that combines a measure of the wet and dry season monthly CVs and the mean annual contribution from baseflows, indicated that part of the variation in IFR workshop results could be explained by differences in the natural hydrological regime (figure 2.2, for example). In analysing the workshop results in this way it was also recognised that they contain a substantial 'noise' component caused by the inherent subjectivity of the BBM process and that any ecological 'signal', reflecting regional differences in biotic response to flow regime differences, was also being treated as noise. It was never, therefore, anticipated that a strong relationship between the hydrological index and the workshop results would be found. The approach is explained below under the same headings used to discuss the detailed methods of setting the reserve, except that there is no implementation phase associated with the desktop method.

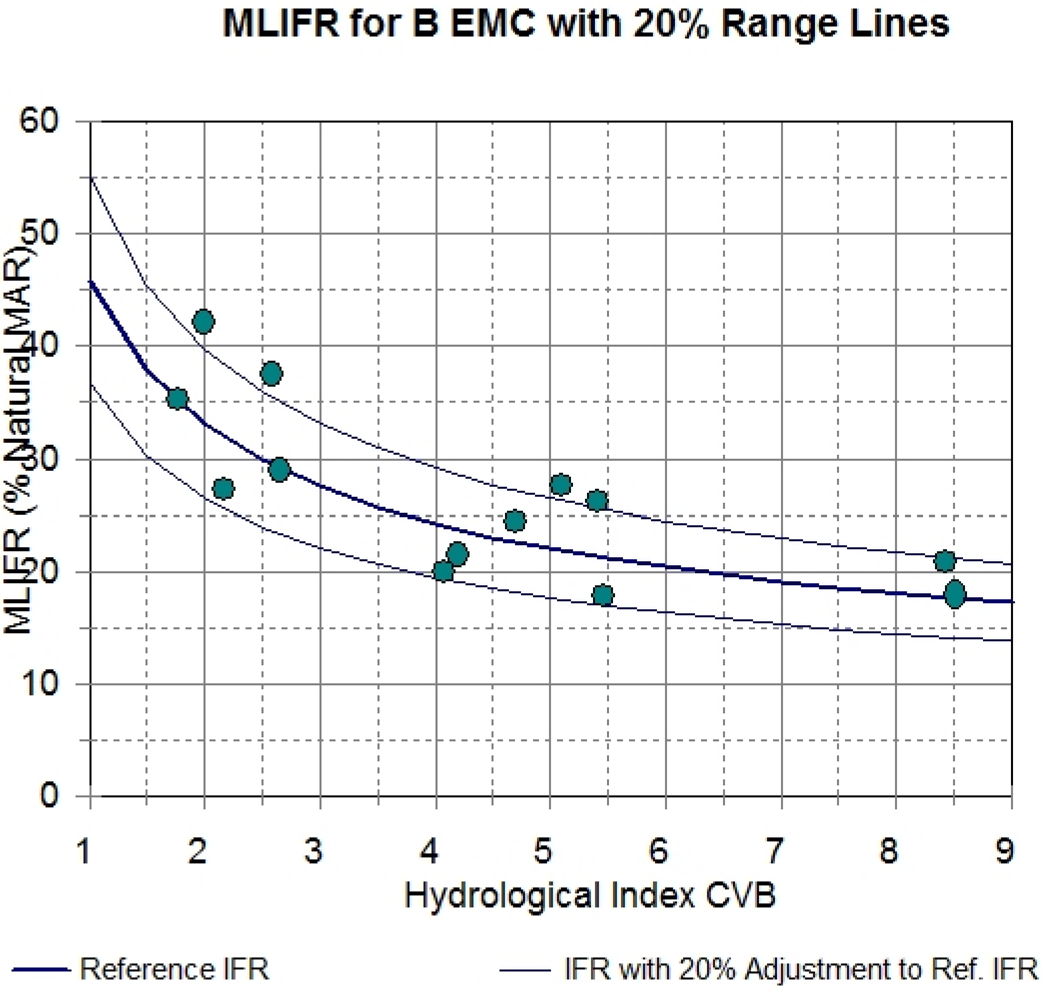


Figure 2.2 Hydrological index CVB (CV/BFI) plotted against maintenance low-flow requirements (MLIFR) for rivers with a B EMC. The bold line represents the estimation equation used within the desktop estimation method, while the ordinary lines represent 20% above and below the bold line. The symbols represent IFR workshop results.

2.3.1 Data generation phase

One of the critical issues related to the desktop approach is that it should be based on readily available hydrological information as no time is allowed for data preparation. For South Africa this means that it must be based upon the quaternary catchment flow data contained within WR90 (Midgley et al., 1994), which consists of 70 years (hydrological years 1920 to 1989) of monthly flow volume time series. However, these time series consist of incremental flows which must be accumulated to create a time series appropriate to outflows from the quaternary catchment at the site of interest.

2.3.2 Data interpretation phase

From the accumulated monthly time series, the necessary CVs are calculated and a baseflow index (BFI - proportion of total flow occurring as baseflow) is estimated from a non-dimensional Q75 (the 75th percentile of the monthly flow duration curve divided by mean monthly flow) and the percentage number of months with zero flows (T0). Separate studies (e.g. Smakhtin and Toulouse, 1998) concluded that the BFI could be estimated from Q75 and T0 using a regression relationship that has a coefficient of determination of greater than 0.9. A further index (CVB) is calculated which is designed to reflect a combination of long (CV) and medium (BFI) term variability, which increases in value from about 1.0 for rivers which are strongly baseflow driven to in excess of 50.0 for rivers which have very low (or close to zero) baseflows and highly variable flows from year to year. The IWR has conducted a number of baseflow contribution studies on South African rivers and from the results has developed regional seasonal distributions of mean baseflow proportions. Part of the data generation phase involves selecting the appropriate region so that the mean monthly flows of the seasonal distribution can be separated into baseflows and higher flows. The CVB index, together with the required EMC, is used to estimate the annual totals of the maintenance and drought, low- and high-flow reserve requirements based on relationships similar to that shown in Figure 2.3 (for maintenance low flows). These annual values are then distributed using the regionalised, seasonal distributions to create the table of monthly values equivalent to the building blocks of the BBM, but expressed as monthly volumes instead of flow rates. Table 2.1 provides an example of the output from the computer program designed to carry out the required calculations.

2.3.3 Design flow requirement stage

The procedures for this phase of the desktop estimate are required to replace the tasks performed using the IFR model during the comprehensive determination. This means that assurance levels have to be associated with the flow volumes of the building blocks. This is achieved using a set of generic 'rule curves' which represent relationships between flow volumes and the percentage of time that these should be equalled or exceeded (equivalent to assurance of supply) in the design time series. The curves are defined for each of the same regions used for the seasonal distributions and for each month of the year. Figure 2.4 illustrates the approach using a screen image of the computer program: the lower curve is for the low flows, the middle curve for the high flow increment, while the upper curve is the calendar month flow duration curve derived from the 70 year time series of natural flows. The drought requirements determine the lower (100% exceedance) limits of the curve, while the shapes of the curves are related to the assurance level at which the maintenance low flows are required and the extent to which low flows are designed to exceed maintenance flows in wet years. Generating a time series of design reserve flows is now a relatively simple matter of stepping through the time series of natural monthly flows, locating the % point position of each on the correct calendar month duration curve and setting the reserve low and high flows to the values at the same % points on the assurance rule curves.

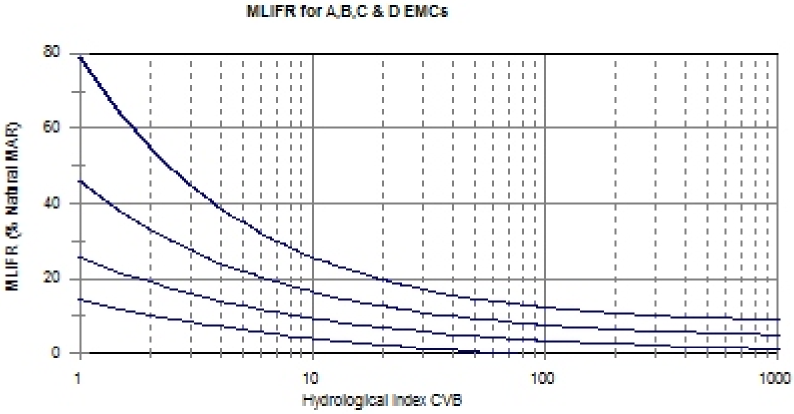


Figure 2.3 Relationship between hydrological index (CVB=CV/BFI) and the annual maintenance low-flow requirement (MLIFR), expressed as % natural MAR. The upper curve is used for an A class and the lower for a D class.

Table 2.1 Example of a summary output from the data interpretation phase of the desktop estimate software.

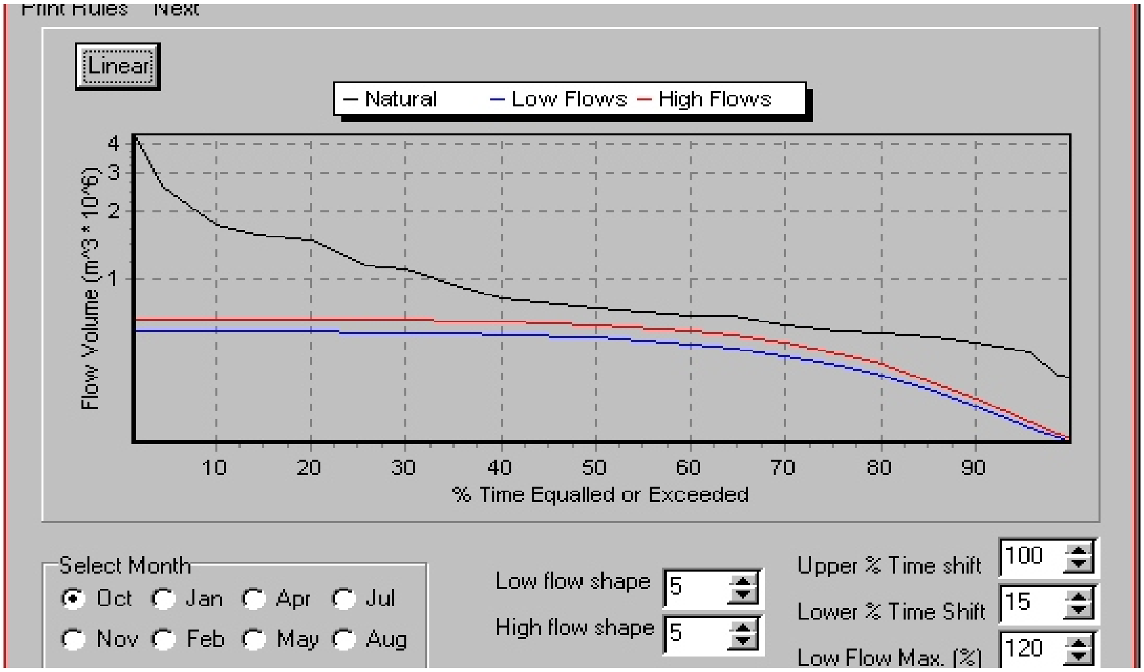
```
IFR estimate for Quaternary Catchments : X32A X32B X32C X32D X32E
Annual Flows (Mill. cu. m or index values):
MAR                 =  100.398
S.Dev.              =   90.268
CV                  =    0.899
Q75                 =    1.930
Q75/MMF             =    0.231
BFI Index           =    0.435
CV(JJA+JFM) Index =      1.679

IFR Management Class = B

Total IFR           =   36.552 (36.41 %MAR)
Maint. Lowflow      =   24.768 (24.67 %MAR)
Drought Lowflow     =    7.509 ( 7.48 %MAR)
Maint. Highflow     =   11.783 (11.74 %MAR)

Monthly Distributions (Mill. cu. m.)
Distribution Type : E.Escarp

Month    Natural Flows           Modified Flows (IFR)
                                 Low flows    High Flows Total Flows
        Mean     SD      CV     Maint.  Drought    Maint.     Maint.
 Oct    1.979   1.324   0.669    0.977   0.366     0.153      1.129
 Nov    4.245   4.552   1.072    1.229   0.426     0.561      1.790
 Dec    9.805  14.513   1.480    1.939   0.596     1.484      3.424
 Jan   17.107  21.713   1.269    2.998   0.849     1.607      4.605
 Feb   23.474  31.971   1.362    3.922   1.070     5.691      9.612
 Mar   20.634  29.504   1.430    4.175   1.130     1.607      5.781
 Apr   10.315  15.836   1.535    3.044   0.860     0.681      3.725
 May    4.287   1.869   0.436    1.830   0.570     0.000      1.830
 Jun    2.854   0.885   0.310    1.400   0.467     0.000      1.400
 Jul    2.180   0.646   0.296    1.192   0.417     0.000      1.192
 Aug    1.842   0.683   0.371    1.087   0.392     0.000      1.087
 Sep    1.675   0.730   0.436    0.976   0.366     0.000      0.976
```



Select Month
● Oct ○ Jan ○ Apr ○ Jul
○ Nov ○ Feb ○ May ○ Aug

Low flow shape 5
High flow shape 5
Upper % Time shift 100
Lower % Time Shift 15
Low Flow Max. (%) 120

Figure 2.4 Screen image of the component of the desktop estimation software that establishes the assurance rule curves. The upper line represents the monthly duration curve of all October flows in the natural time series; the lower line the rule curve for low flows and the middle line the incremental requirement for high flows.

2.3.4 Scenario planning phase

Although this is not really appropriate to the desktop approach, the output from the computer program is fully compatible with the water resource system yield models used within South Africa and the yield implications of changing ecological management class or the shape of the assurance rule curves, for example, can be readily assessed

The software created for the desktop approach is also applicable to the rapid determination method as the user can modify the generic estimates at all stages in the process.

2.4 General comments

Many of the hydrological models and time series analysis and display routines that form part of HYMAS were developed for generic purposes over some 8 years starting in the late 1980s. The fact that they are able to make a major contribution to a developing field of water resource management more than 10 years after they were initially conceived is a testament to their robustness and resilience. One of the other major South African developments that also occurred during the same period was the creation of the national database of naturalised monthly streamflow time series through the WR90 project (Midgley et al., 1994). While these data have to be accepted as not being always perfect, without them rapid planning estimates at a national scale, such as those that form part of the desktop estimate approach, would not be possible. A further contributing factor is the strong tradition of systems modelling that has formed part of DWAF water resource planning and management practice for some time. Without such models and their developer's ability to modify them to cater for the reserve requirements, output from the IFR model or the desktop estimation software would have existed in a vacuum.

A large part of hydrological research in South Africa over the last two decades has been orientated toward the solution of practical water resource problems. One measure of the success of these research programmes could be how well they have prepared the country to respond to new challenges. The speed with which the hydrological community (in cooperation with other water scientists) has responded to the challenges of the new Water Act suggests that these programmes have been very successful indeed.

Some new approaches to carrying out instream flow assessments in southern Africa are beginning to emerge, largely within the context of the Lesotho highlands scheme. It is understood that the new approaches are intended to address some of the subjectivity inherent in the BBM and the difficulty of determining reserve requirements for different EMCs on the same river (Dr J King, Pers.Comm). While these new methods will inevitably require new approaches to analysing the hydrological information, the general comments made in this paper are still likely to be appropriate and many of the existing methodologies will still be applicable.

3. A DECISION SUPPORT SYSTEM FOR AN INITIAL 'LOW-CONFIDENCE' ESTIMATE OF THE QUANTITY COMPONENT OF THE RESERVE FOR RIVERS

This section of the report is designed to be read by users who are reasonably familiar with the basic concepts underlying the quantification of instream flow requirements (IFRs) and the methods used within South Africa. It also assumes some familiarity with the concepts of the 'Ecological Reserve' and the role that it plays in the new legislation relating to management of water resources in South Africa. Readers who are unfamiliar with these concepts are recommended to the reference section where a number of recent publications that are referred to in this report are listed .

During the late 1980s and 1990s, the IFR for rivers in South Africa were quantified using the 'Building Block Methodology' (BBM) which is summarised in King and Louw (1998) and fully described by King, et al., 1999 and will be briefly summarised later in this document. As the new South African Water Law was developed during 1997 and 1998 in preparation for its implementation starting in 1999, it became apparent that more rapid methods of assessment were required. This led to the concepts of the 'Planning Estimate' and the 'Preliminary Reserve'. These are now referred to as the 'Desktop estimate' and the 'Intermediate determination', while the most detailed type of study is called a 'Comprehensive determination'.

The desktop estimate began to be viewed as an initial low-confidence estimate that could be applied very rapidly at a large number of sites to provide a first guess at the likely amounts and distribution of water that is required to sustain the ecology in a given condition. However, it was always made clear that such an estimate should never be considered to be the final value to be used for managing a river system. The main purpose of the desktop estimate concept was to generate initial values for all the quaternary catchments of the country to provide input to the National Water Balance Model (van Rooyen and de Jager, 1998), which was developed during 1998 and 1999 to provide a national database on the existing available yield from all the river systems of South Africa. The concept was to determine the yield from the natural flow regimes less that water which is already being used by existing water resource developments, existing streamflow reduction activities (afforestation, etc.) and that which is required to satisfy the reserve (for both basic human needs and the ecology). It was clear that the application of the more detailed methods to so many sites (1946 quaternary catchments) would be impossible and that a very rapid method was required. It was also clear that our knowledge and understanding of the variability of eco-hydrological relationships throughout the country is not advanced enough to be able to develop a method that would provide anything more than a low-confidence estimate.

The initial implementation of the new Water Act during 1999 also meant that there would be many occasions when estimates with much higher confidence would be required and where there would not be enough time (or financial resources) to apply the full BBM. The intermediate determination methodology was therefore developed as an approach which was based on the same principles as the BBM, but uses fewer resources of time and money. The details of the intermediate determination and its development are documented on the web site of the IWQS (Institute for Water Quality Studies - http://iwqs.pwv.gov.za/cgi-bin/password.pl).

In establishing a possible method for the desktop estimate the authors considered that it should form the lower end of a continuum of approaches, the BBM (or equivalent) forming the upper end and all the methods being based on the same fundamental principles of relating ecological response to changes in flow regimes. The strength of such a system should then be that developments in understanding that emerge from the application of the more complex approaches would 'feedback' to the simpler approaches and improve the confidence of the estimates. A further consideration in developing the desktop estimate was that, while it is mainly designed for application of regional 'generic' type relationships at a large number of sites, it should also be applicable at sites where additional information is available and where the results of the generic relationships could be modified to improve the confidence of a quick estimate. Thus, the requirements of the decision support system should include a facility for 'manual override'.

This part of the report represents a 'User Manual' to guide a potential user through the use of the computer programs that comprise the DSS, as well as an explanation of the source of the components of the DSS. The detail of these components are likely to change quite rapidly during the initial period of the DSS usage and all prospective users are advised to consult the web site of the Institute for Water Research (http://www.ru.ac.za/departments/iwr) for the most up-to-date version of this manual (see date of latest revision on the first page). More detail on the nature of each of the revisions is included in the headings of the main methodology sections of this document. Revised versions of the software and associated databases will also be available from the IWR (consult the web site for details).

The final paragraph of this introduction provides a warning to all potential users and a disclaimer from the authors.

> The results given by the generic regional relationships that form the default options of the DSS have to be considered as initial low-confidence estimates and should not be considered to be the final answer. While every attempt has been made by the developers of the method to incorporate as much as possible of the current understanding of the relationships between ecological functioning and flow regimes of rivers, there is no guarantee that the estimates given by the DSS will be close to the estimates provided by methods based on the inputs from a range of ecological specialists and more detailed site-specific information.
>
> The results are, therefore, NOT scientifically defensible and anyone ignoring this warning and using them out of context does so at their own risk.

3.1 Structure of the DSS

The DSS consists of two computer programs written using the DELPHI language, as well as some accompanying data files and database tables. The first program (***RESDSS***) is designed for site-specific applications of the methodology and incorporates various facilities for user intervention and the ability to manually adjust some of the estimated values. The second program (***SARES***) provides a facility to rapidly access an initial low-confidence estimate of the quantity component of the Reserve for rivers at the outlet of any quaternary catchment in the country, but provides for virtually no user intervention.

Both programs rely on six basic procedures to provide the required information. These are summarised below, but are discussed in more detail within later sections of this document.

> It is the detail of these later sections that is most likely to change during the revision process and each section heading is followed by a date that represents the most recent revision. These dates can be compared with the date of the version of the software.

A further two programs (***WR90MAN*** and ***IFREDIT***) are provided for some database management functions. ***WR90MAN*** allows the Paradox database of quaternary WR90 data to be constructed and edited, as well as individual quaternary catchment incremental flow-time series to be viewed. ***IFREDIT*** provides a program untility for entering the results of IFR workshops into a Paradox database, which is then available if the user wishes to override the monthly table of ecological flow requirements that are estimated from the regional generic relationships (see sections 3.1.3 and 3.1.4).

3.1.1 Natural time series preparation

The method has to be based on readily available information and the only flow data that have been generated countrywide are the monthly time series for quaternary catchments included in WR90 (Midgley, et al., 1994). The flow-time series provided are incremental flows for all 1946 quaternary catchments covering South Africa, Lesotho and Swaziland, while for IFR determination, accumulated flows at quaternary outlets are required.

Within ***RESDSS*** the user selects the quaternary catchments to be included, either by selecting a group of files from the WR90 CD ROM (or alternative source of the same files), or a group of records from the paradox database of WR90 flow data compiled by the IWR (and available with the DSS software). The individual time series are then simply accumulated into a single time series representing flow at the outlet of the most downstream quaternary. It is, therefore, the user's responsibility to select the appropriate files or database records. ***It has now been generally accepted that there are problems with some of the original WR90 time series related to the way in which they were naturalised to account for afforestation influences.*** New versions of the data sets have been generated by Ninham Shand for the National Water Balance Project and have been incorporated into the paradox database included with the software, while the old versions can still be accessed from the WR90 CD ROM.

One problem with the simple accumulation of quaternary time series is that there is ***no account taken of natural losses that might occur during the transmission of flows generated upstream as they pass through successive downstream quaternary catchments***. This is unlikely to be a problem in many catchments, particularly in the wetter parts of the country and where the total catchment area is not very large (less than several thousand km^2). However, this becomes an important issue where headwaters of catchments lie in relatively wet, high runoff areas and then pass through drier parts of the country. No account of such losses is allowed for in ***RESDSS***, but the user is not restricted to using standard WR90 data sets. For more accurate representation of accumulated streamflow regimes in such cases, users are recommended to generate their own time series, the only restriction being that the file format should be the same as the standard WR90 data files.

As ***SARES*** is designed to be a stand-alone method using WR90 data (original or updated) without user intervention, it was necessary to include an attempt to account for losses during accumulation. The accumulation process is automatic and is based on a file representing the 'tree structure' of quaternary catchments (provided with the software), while losses are estimated using a simple approach based on mean annual net evaporation as well as the sizes of the quaternary catchment and the total accumulated catchment. The details of this approach are provided in Section 3.2.

3.1.2 Setting the ecological management class

Within ***SARES*** the default ecological management classes (EMCs) for all the quaternary catchments has been derived from the Provincial assessments carried out as part of the National Water Balance Model project. These are meant to be the first guesses of the likely EMCs, but include no consideration of the views of local stakeholders. There are no procedures within ***SARES*** for determining the EMC, but the classes can be changed and the Reserve requirements regenerated if necessary.

Within ***RESDSS*** both the present status and the default management class can be determined following the procedures of Kemper and Kleynhans (1998) and Kleynhans, et al. (1998). The present status of the instream and riparian components are determined using the habitat integrity scoring system of Kemper and Kleynhans (1998) which is usually applied on a river reach (about 5 km long) basis, prior to IFR workshops. The default management class determination is based on the ecological importance and sensitivity scoring approach of Kleynhans, et al. (1998). More details are provided in Section 3.3, although the original references should be consulted if the user requires more information about the background and motivation for these approaches.

3.1.3 Annual IFR component determination

The BBM normally quantifies monthly values for four components of the IFR. These are the maintenance and drought low flow requirements and the maintenance and drought high flow requirements. The first step in the DSS procedure is to estimate the annual values of these four components as a percentage of the mean annual runoff of the natural flow regime. The estimation equations were initially based on an analysis of past IFR results in which reasonable confidence could be expressed in the outcome. This process was totally based on the hydrological characteristics of the flow regimes and is documented in Hughes, et al. (1998), a copy of which is included on the IWR web site.

Subsequent to the development of the initial estimation approaches, a short-term project (financed by the WRC) was started to try and build more ecological information into the estimation procedures. The current (or final) results of that project are given in Münster and Hughes (1999), also included on the web site. Section 3.4 provides detailed information on the estimation equations for the annual Reserve requirements used within the current DSS.

3.1.4 Monthly distribution determination

The annual values of the Reserve components are based on a single set of estimation equations that are applied to all parts of the country (although later revisions may include regional corrections), while the distribution of these values into monthly values will inevitably vary according to regional flow regime characteristics. The monthly distribution procedures are therefore based on regionalised sets of parameters which have been determined from a countrywide analysis of the seasonal baseflow and highflow characteristics of South African rivers. Within ***RESDSS*** the user is required to select the region most appropriate to the individual river system being dealt with, while in ***SARES*** the default region is provided as a field within the database. A GIS coverage and text file of the regions associated with the outlet of all quaternary catchments is provided with the software, while more details about the regionalisation process is provided in Sections 3.5 and 3.6. It is now possible to select an existing IFR workshop result from a database and replace the annual values and monthly distribution with those volumes that were set by the specialists.

3.1.5 Establishing the assurance rules

Before the monthly distributions of IFRs can be considered useful for water resource planning and management, it is necessary to determine a basis for deciding when the maintenance (or above) components of the recommended flows should apply and when lower flows (i.e. down to and including the drought recommendations) should apply. During 1997 and 1998, these decisions were made during a number of workshops on the basis of a model (Hughes, et al., 1997) which allows a set of rules to be applied and the results visualised by the various specialists through representative time series of IFR- modified flows. The model could then be 'calibrated' until the specialists were satisfied that the rules were generating an adequate pattern of frequency of occurrence of maintenance and drought flows. A similar system has been incorporated into the DSS based on monthly data and these are referred to as 'Assurance Rules'. They are essentially curves relating the % of time that certain flows will be equalled or exceeded in the modified flow regime and can be used in conjunction with the natural time series and associated flow duration curves to generate representative time series of flows required to satisfy the Reserve requirements.

The same regions referred to in Section 3.1.4 have been used to define generic curve shapes on the basis of the hydrological characteristics of the natural flow regimes of the regions and following guidelines and principles discussed during past IFR workshops with a number of specialists. The generic curve shapes are fixed within the ***SARES*** program, but within the ***RESDSS*** program they form the default shapes, which can be modified by the user if necessary. More details and example curves are provided within Section 3.7.

3.1.6 Summarising the results and generating output data

The final result of the application of the DSS using either program is a representative time series of monthly flow volumes (the same length as that used to represent the natural flow regime) recommended for the quantity component of the Ecological Reserve for the selected management class. However, both programs can also generate a table of assurance rules that can be used by the Water Resource Yield Model, a systems model used extensively by DWAF (and associated consultants) for determining the yields of complex systems under alternative scenarios of development and water use. Section 3.8 provides more details of the output and summary options.

3.2 Natural time series preparation (*dated July 1999*)

To conform to the principle that the DSS should be applicable to as many sites within South Africa as possible without the necessity to expend resources to prepare hydrological data, the system is based on the use of time series data with a resolution of 1 month. Such data are readily available for all quaternary catchments within South Africa, Swaziland and Lesotho from the WR90 (Midgley, et al., 1994) CD ROM which is available from the Water Research Commission. However, it has been recently recognised that the way in which these data were generated in catchments where there have been significant afforestation influences does not conform to our present understanding of the differential influences of afforestation on low and high flows. These data sets are, therefore, currently being updated and corrected time series are expected to be available in the near future.

A further problem with the use of WR90 data is that any analyses will inevitably be restricted to quaternary scale catchments. While many of the results generated by the DSS are provided as values in % MAR and can therefore be scaled down, there are currently no clearly defined guidelines for down-scaling from quaternary flow regimes to smaller catchments.

The final problem with the use of WR90 data is that the raw time series are only for incremental flows (i.e. those flows generated within the quaternary catchment itself) and no guidelines are provided for estimating transmission losses when a number of incremental flow time series are accumulated to provide a total time series at the outlet of a quaternary catchment.

The WR90 data that are currently used by the Institute for Water Research are the updated time series that have modified afforestation influences included in them. This modification arose due to a change in the approach used to naturalise the flow regimes for those catchments affected by afforestation. The old approach used during the initial compilation of the WR90 data sets has been changed.

3.2.1 Within *RESDSS* (Site specific applications*)*

RESDSS allows the monthly time series that will be used to create a representative time series of natural flows at the site of interest to be accessed from two different sources.

Individual text data files:

A user is not restricted to using WR90 files but the format of the input files has to be identical in most respects to the WR90 data files contained on the CD ROM and illustrated in Table 3.1. The following are the critical format specifications :

☐ There must be three lines of text (blank lines are acceptable) before the real data starts.

☐ The 'R' of region in the first line is used to recognise the start of the data title.

☐ The ':' before the quaternary catchment number is used to recognise the start of the quaternary ID.

☐ The year must be given as a full four digits.

☐ The monthly data must start with October.

☐ The 12 monthly values must be separated by a least one space.

☐ The annual total at the end of each line is optional.

☐ The monthly values must be given in $m^3 * 10^6$ (million cubic metres).

☐ WR90 data start in 1920 and are 70 years long. This is not fixed and the start year and length of record can be varied.

☐ The average monthly values and any text comment lines at the bottom of the file are optional.

Table 3.1 Format of text file input to ***RESDSS***

```
REGION C  SIMULATED NATURAL RUNOFF FOR QUATERNARY : C11A    (MILLION CUBIC METRES)

YEAR    OCT     NOV     DEC     JAN     FEB     MAR     APR     MAY     JUN     JUL     AUG     SEP     TOTAL
1920   46.63   12.42    1.04     .53     .59   27.89    9.56     .22     .11     .09     .06     .07     99.21
1921    5.48   43.16   17.27    1.75     .59     .50     .25     .24     .31     .23     .26     .26     70.31
1922   45.31   28.34   14.14   39.45   12.55     .23     .08     .07     .08     .10     .09     .05    140.50
.
.
.
1987   25.92   48.20   14.32     .77     .43     .39     .28     .13     .14     .21     .16     .19     91.14
1988   17.39    6.20    4.72    1.95     .95     .51     .14     .13     .70     .62     .25     .10     33.66
1989     .23   25.22    9.06     .42     .81     .89    1.18     .66     .19     .09     .07     .04     38.82
AVE     5.06   12.26   10.01   11.00    7.32    4.55    2.20     .79     .30     .24     .20     .65     54.56

NOTE: YEAR 1920 IS YEAR OCT 1920 THROUGH SEPT 1921
```

Using this option it is possible to prepare time series data files that incorporate losses down a system, or that represent flow regimes at sub-quaternary scales.

The WR90 data files do not contain any information about the area of the quaternary catchment and these areas are not explicitly required by the program. However, they can be entered manually by highlighting the quaternary catchment in the list displayed on the screen and entering the area in the edit box provided. The total area will then be accumulated as quaternary data sets are added.

IWR database records:

The second available option is to access WR90 data from a Paradox database (with a table name of ***WR90***) that has been established by the Institute for Water Research. These data are stored as BLOBs (Binary Large Objects) together with information on the quaternary name, catchment area, hydrological zone, response zone, MAR, MAP and MAE for all the quaternary catchments in the country. An additional program (***WR90MAN***) is available to provide some facilities to manage and edit the database. If this option is chosen, the user is restricted to selecting only WR90 data that starts in 1920 and extends for 70 years.

Regardless of the source of the data, all the time series that are selected are then accumulated into a single total time series. While both sources can be mixed (i.e. some data from text files and some from database records), ***it should be made clear that they should all start with the same year and have the same length record***. There are no facilities within the program at present to filter out only those data that are coincident across all the selected files/records. ***There is a restriction in the program that a maximum of 50 original time series data sets can be accumulated.***

When all the original data sets have been selected the accumulated time series data are determined and some summary statistics displayed on the screen. Further options allow the total time series to be written to a text file (WR90 format) for re-use later and for all the incremental time series to be cleared and the accumulation process started again.

A recent addition to the program allows the mean annual runoff of the accumulated flow time series to be changed by the user through applying a percentage correction factor. The individual months of the time series are adjusted by the same percentage value, the effect being a simple constant percentage correction.

This may be required in those cases where the site of interest is not at an exact quaternary boundary and the user needs to make an adjustment to the overall natural flow volume.

3.2.2 Within SARES

Table 3.2 Part of the quaternary 'Tree Structure' text file used to define the upstream catchments above all quaternary catchments in the country (Sabie catchment).

```
X31A   0
X31B   1
 1  1  X31A
X31C   0
X31D   2
 1  2  X31B  X31C
 2  1  X31A
X31E   0
X31F   0
X31G   1
 1  2  X31E  X31F
X31H   0
X31J   1
 1  1  X31H
X31K   3
 1  3  X31D  X31G  X31J
 2  5  X31B  X31C  X31E  X31F  X31H
 3  1  X31A
X31L   0
X31M   4
 1  2  X31K  X31L
 2  3  X31D  X31G  X31J
 3  5  X31B  X31C  X31E  X31F  X31H
 4  1  X31A
```

The ***SARES*** program is designed to operate only on WR90 data from the IWR's Paradox database (table ***WR90***) and the total natural time series for the outlet of all quaternary catchments are created automatically by the program from a data file containing the 'Tree Structure' (or linkage structure) which defines all the upstream quaternaries (Table 3.2).

As each upstream quaternary is loaded automatically in the program (starting with the headwater areas), a potential mean annual transmission loss value is also estimated on the basis of the mean annual net evaporation and two size factors. The first size factor (*LENGTH*) is used to represent the channel length within the quaternary and is estimated (in units of km) from :

$$\textit{LENGTH} = (\textit{Quaternary area})^{0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 3.1}$$

The second size factor (*WIDTH*) is used to represent the channel and riparian width and is estimated (in units of m) from :

$$\textit{WIDTH} = 4.5 * (\textit{Total Upstream Area})^{0.32} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 3.2}$$

Mean annual losses (*MAL*) are then estimated from the following equation :

$$MAL = (MAE - MAP) * LENGTH * WIDTH * 10^{-6} \quad \text{Eq. 3.3}$$

Where MAE and MAP are mean annual evaporation and rainfall depths (mm) respectively; the units of MAL are $m^3 * 10^6$
and MAL is limited to positive values.

The value of MAL is compared with the accumulated MAR at the upstream end of the quaternary and if MAR is less than MAL, then MAL is reduced to the accumulated MAR (i.e. it is not possible to have more losses than water available). Individual accumulated monthly values are then reduced by 1/12th of the MAL.

While the approach to estimating losses clearly has its limitations and does not adequately cater for seasonal, nor dry/wet year variations, it does at least provide an estimate that is better than not allowing for losses at all. The results for various points along the lower Orange River have been compared to estimates of losses given for the same sites by McKenzie and Craig (1997) and there is reasonable agreement (however, the power and scale parameters in the estimate of width was largely based on the Orange River estimates, such that this agreement was inevitable).

The ***SARES*** program generates (or updates) a database table (named ***WR90RES***) and one of the fields is the total MAL of the accumulated flow record at the quaternary outlet. Users are therefore able to compare these values with the accumulated MAR and their own perceptions of likely losses within specific river systems. ***Any comments on practical (and simple) methods that could be applied to improve the loss estimates will be gratefully received by the developers***.

3.3 Setting the ecological management class (*dated March 1999*)

Within the ***SARES*** program, the Ecological Management Class (EMC) is specified within a field in the database table using an integer value, where 0 represents class A, 1 class A/B and the lowest class possible is 6 or class D. In both programs classes intermediate between the standard classes of A, B, C and D have been used to extend the flexibility of the estimates and to allow for borderline cases. Thus, A/B (or 1), B/C (or 3) and C/D (or 5) represent those situations where the EMC is expected to lie at the upper end of the lower class or the lower end of the upper class.

SARES assumes that the EMC has been previously determined and forms part of both the **WR90** and ***WR90RES*** database tables. The program has no facilities for estimating the class. ***If the class is changed within the database then the IFR estimates should be re-generated to ensure that the other information contained within the database table is compatible with the current EMC.***

RESDSS includes specific components to allow the EMC (and Present Status) to be estimated, although these procedures need to be carefully checked.

3.3.1 Present status estimation

These procedures are based on the methodology presented in Kemper and Kleynhans (1998) using a scoring system to assess the habitat integrity of a reach of a river. The details of and motivation for the approach are available from the original reference, but essentially, the method relies on being able to specify scores for various impact criteria (water abstractions, flow modification, channel modification, indigenous vegetation removal, etc.) on either the instream or riparian environments, or both.

The basis of the scoring system is summarised in Table 3.3 and the program allows the user to first specify the impact class and then adjust the final score within the given ranges.

Table 3.3 Habitat integrity scoring system according to Kemper and Kleynhans (1998)

Impact Class	Range of Scores
None	0
Small	1 to 5
Moderate	6 to 10
Large	11 to 15
Serious	16 to 20
Critical	21 to 25

Once the scores for all the impact criteria for instream and riparian environments have been entered a series of weighting factors are applied and the preliminary present status class is estimated. The criteria and scoring weights are given in Table 3.4.

The score contribution of each criterion is calculated as follows :

Weight * Score / Maximum Score . . . . Eq. 3.4

After which they are all summed to provide a total for both instream and riparian environments. The present status can then be estimated within ***RESDSS*** using the guidelines given in Table 3.5. The fact that these are not based on exactly the same scoring system as the original Kemper and Kleynhans (1998) procedure is not really that important as the Present Status class is only used to define a default EMC. The user can then override the default value as required.

Table 3.4 Criteria and scoring weights for habitat integrity (Kemper and Kleynhans, 1998)

Instream Zone	Weight	Riparian Zone	Weight
Water abstraction	14	Water abstraction	13
Flow modification	13	Flow modification	12
Bed modification	13		
Channel modification	13	Channel modification	12
Water quality	14	Water quality	13
Inundation	10	Inundation	11
Exotic macrophytes	9	Bank erosion	14

Instream Zone	Weight	Riparian Zone	Weight
Exotic fauna	8	Exotic vegetation encroachment	12
Solid waste disposal	6	Indigenous vegetation removal	13
TOTAL	100	TOTAL	100

Table 3.5 Preliminary present status classes based on total scores

Class	Brief Description	Score
A	Unmodified	94 to 100
A/B	Transitional A to B	88 to 93
B	Largely natural with few modifications	82 to 87
B/C	Transitional B to C	75 to 81
C	Moderately modified	65 to 74
C/D	Transitional C to D	55 to 64
D	Largely modified	45 to 54
D/E	Transitional D to E	35 to 44
E	Natural habitat loss extensive	25 to 34
E/F	Transitional E to F	15 to 24
F	Modifications at a critical level	0 to 14

Any number of reaches can be specified in the program component that sets the present status scores, although this is not the normal procedure by which an estimate of the EMC would be derived. The normal procedure would be to use the Ecological Importance and Sensitivity procedure outlined in the following section.

3.3.2 Ecological Management Class by Ecological Importance and Sensitivity

The procedures explained in Kleynhans et al. (1998) have been incorporated into the ***RESDSS*** program as accurately as possible (Tables 3.6 and 3.7), but there still appears to be some inconsistencies due largely to the developers mis-interpretation of the use of the scoring system. ***These need to be resolved before the scoring system within RESDSS can be used with any confidence. The approach generally used was changed during July/August 1999 but this has yet to be incorporated into the DSS.***

Even if the current system that is coded into ***RESDSS*** is used, the final management class to be used in setting the IFR values can be changed by the user.

The average of the first 8 category scores is used to estimate the EMC, with the limitation that if this average is lower than either of the scores for the modifying determinants then the highest of their scores is used. There are also a few other over-riding factors that control the final score.

Table 3.6 presents the basis of the scoring system used by Kleynhans et al. (1998) to determine the present status of a river. The class is based on the average of the scores for the 5 criteria.

Table 3.6 Scoring system for EMC according to Kleynhans et al. (1998)

Category/criterion	Score: high = Important or Sensitive
Indigenous Instream and Riparian Biota	
Rare and endangered species	0 to 4
Unique biota	0 to 4
Intolerant biota	0 to 4
Species/Taxon richness	0 to 4
Aquatic and Riparian Habitats	
Diversity of habitat types and features	0 to 4
Refuge value of habitat types	0 to 4
Sensitivity to flow changes	0 to 4
Sensitivity to water quality changes	0 to 4
Modifying Determinants	
Migration route/corridor - instream and riparian	0 to 4
Presence or importance of conservation and natural areas	0 to 4

Table 3.7 Present status scoring system according to Kleynhans et al. (1998)

Category/criterion	Score: High = Natural
Deviation from natural of :	
Flow	0 to 5
Inundation	0 to 5
Water quality	0 to 5
Stream bed condition	0 to 5
Riparian condition	0 to 5

3.4 Annual IFR component determination (*dated August 1999*)

The paper by Hughes, et al. (1998) explains the background and original basis of the approach that was used to develop the estimation equations for the annual values of the IFR components. These components are the low and high flow maintenance quantities and the high and low flow drought quantities. The original approach was to look for a hydrological index that was logically reasonable and could be used to explain at least some of the variation in IFR requirements between sites where the same Ecological Management Class was assumed.

The basic assumption of the approach is that variations between sites would be the function of variations in hydrological regime characteristics, specific ecological functioning, flow-habitat relationships determined by channel-physical characteristics and noise-related to the inherently subjective (expert judgement) nature of the IFR workshop process. At the time at which the approach was being developed the only component of that functional relationship that had the potential to be readily quantified was the hydrological regime characteristics. The remaining components would then have to be treated as 'noise' until more clarity could be obtained on how best to quantify them. ***It is therefore inevitable that the initial relationships developed would have a great deal of scatter and that their use to predict likely IFR results would have to be treated with caution and assumed to represent initial low-confidence estimates***.

Ideal situation :

IFR = F(Hydrological + F(Ecological + F(Flow-habitat + Noise
regime) functioning) Relationships)

Current situation :

IFR = F(Hydrological + Noise
regime)

To move closer to the ideal situation, more information is required about regional eco-hydrological relationships and how these are affected by changes in the physical characteristics of channels brought about by flow regime modifications (see Münster & Hughes, 1999).

Two hydrological characteristics were selected as being logically relevant to estimating IFR components, given the constraint that they also have to be readily quantifiable from available streamflow time series. Section 3 indicates that the default source of flow data is the WR90 (original or updated) database of monthly flows. The two characteristics are measures of flow variability and that proportion of the total flow that occurs as baseflow.

3.4.1 Flow variability index

The flow variability index selected has been designed to summarise variability within the wet and dry seasons and is based on the average coefficient of variation (Standard Deviation/Mean) for the three main wet season months and the three main dry season months (excluding those that have zero mean monthly flows). The actual index used is the sum of these two means. Where more than two of the months in the dry season experience zero flows all the time (i.e. means and standard deviations of zero), a further month (earlier or later in the year) is used to estimate the index so that the average dry season CV is based on at least two months.

The assumption is that rivers with a high degree of variability (high index value) will require lower proportions of their natural mean annual runoff (within a single EMC) because they are used to experiencing such conditions. More reliably flowing and less variable rivers are assumed to be less well adjusted to frequent low extremes and would, therefore, be expected to require a higher proportion of their mean annual runoff in order to sustain ecological functioning.

3.4.2 Index of baseflow

A hydrological definition of baseflow relates to the extent to which rainfall, occurring in relatively short duration storms, is buffered through various runoff generation processes to produce streamflow patterns which are usually of longer (if not continuous) duration. Some of the rainfall passes through sub-surface storages (ground water), which respond and drain relatively slowly, producing the low amplitude component of streamflow hydrographs. The high amplitude streamflow response is derived from surface runoff processes, or drainage from near surface and rapidly reacting storages. The assumption is made that for ecological purposes the relatively smooth 'seasonal' baseflow response is the relevant streamflow characteristic to consider when attempting to quantify the low-flow component of the IFR.

There are various methods available for separating the baseflow component from a time series of total flow, most of which operate with daily time steps or lower. Smakhtin and Watkins (1997) discuss these in more detail and the procedures are not explained here. What is important is that the procedures used in the DSS have to be based on widely available monthly data and the standard separation procedures are no longer valid. Fortunately, Smakhtin and Toulouse (1998) found that there is a consistent relationship between low flow indices extracted from flow duration curves and the baseflow proportion of total flow when daily flow data are used. There is also a reasonably consistent relationship between low flow indices extracted from flow duration curves compiled using monthly data and the same indices taken from daily flow duration curves.

Specifically, for South African rivers, the following relationship between Q75 (the flow equalled or exceeded 75% of the time) based on monthly and daily data can be assumed to apply :

$$Q75D = 0.89 * Q75M - 0.0099 \qquad \text{Eq. 3.5}$$

where Q75D and Q75M are the 75th percentiles of the daily and monthly flow duration curve, respectively, using non-dimensional flow data (i.e. flows divided by mean daily or mean monthly flow)

The R^2 value for this relationship is 0.96, suggesting an extremely close relationship between the daily and monthly Q75 values. Furthermore, the following relationship between BFI (proportion of total flow occurring as baseflow - a value between 0 and 1) and Q75D can be considered to be applicable over a wide range of South African rivers if the correction using T0 (percentage number of months with zero flow) is included to account for ephemeral or seasonal flow regimes (the R^2 value for this relationship is 0.92):

$$BFI = 0.832 * Q75D + 0.272 - 0.006 * T0 \qquad \text{Eq. 3.6}$$

The assumption has been made that rivers with high baseflow indices will require higher proportions of their natural mean annual runoff because such flow regimes have lower degrees of short term variability. Lower baseflow indices suggest flow regimes where frequent periods of low flow occur between higher flow, short duration events.

An Arc View spatial coverage of BFI and estimated mean annual baseflow depth (mm) for incremental quaternary catchments is available with the programs and associated databases.

3.4.3 A combined index and estimation of maintenance IFR components

The variability index can vary from a small number of less than 1 to quite a large number (above 10) and decreasing IFR values are expected with increasing variability. The BFI is constrained to lie between 0 and 1 and decreasing IFR values are expected with decreasing BFI. Therefore, the logical combination of the two indices (CVB) is variability divided by BFI; generating an index that can lie between a number less than 1 to a number close to infinity (i.e. no baseflows).

Table 3.8 illustrates the range of index values for the 1946 quaternary catchments (based on accumulated flow-time series) covering the whole of South Africa, Swaziland and Lesotho. An Arc View coverage of these data is available with the software and other databases.

The experience base (past IFR workshop results) upon which to base estimation equations using the CVB index only includes rivers with index values up to 9.0, while most of them are in the region of 1.8 to 6.0 (representing only about 30% of possible conditions throughout the country). ***There will inevitably be a great deal of uncertainty associated with applying any estimation equations outside the area of experience and particularly in the drier and more variable flow regimes with index values of greater than 10. This issue was partially addressed during the latter half of 1999 when quick IFR estimates were made for several rivers (in both the Northern Province and the Eastern Cape) with quite high index values (> 10).***

The original equations used were later found to be difficult to apply at high index values and generated negative values (corrected to zero) for more than 20% of the catchments. These have now been modified to generate positive estimates for the IFR components, even at relatively high CVB index values.

Table 3.8 Range of CVB index values for all quaternary catchments.

CVB index	No. of catchments	% of catchments	Cumulative %
< 1.0	1	0.1	0.1
1.0 to < 2.0	47	2.4	2.5
2.0 to < 4.0	187	9.6	12.1
4.0 to < 6.0	387	19.9	32.0
6.0 to < 10.0	390	20.0	52.0

CVB index	No. of catchments	% of catchments	Cumulative %
10.0 to < 15.0	212	10.9	62.9
15.0 to < 25.0	125	6.4	69.3
25.0 to < 50.0	207	10.6	80.0
50.0 to < 75.0	270	13.9	93.9
75.0 to < 100.0	30	1.5	95.4
> 100.0	90	4.6	100.0

Maintenance low flow requirements

Figures 3.1 and 3.2 illustrate the shape of the estimation relationships for maintenance low flow requirements (for EMCs A, B, C and D) over CVB ranges of 1 to 10 and 1 to 1000, respectively, while the actual equation is given below and the parameters of the equation for all EMCs are given in Table 3.9.

Estimation equation for MLIFR (maintenance low flow total as % natural MAR) :

$$MLIFR = LP4 + (LP1 * LP2) / (CVB^{LP3})^{(1 - LP1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 3.7}$$

Table 3.9 Parameter values of the equation to estimate the annual total maintenance low flows.

Parameter	Ecological Management Class						
	A	A/B	B	B/C	C	C/D	D
LP1	0.900	0.905	0.910	0.915	0.920	0.925	0.930
LP2	79	61	46	37	28	24	20
LP3	6.00	5.90	5.80	5.60	5.40	5.25	5.10
LP4	8.0	6.0	4.0	2.0	0.0	-2.0	-4.0

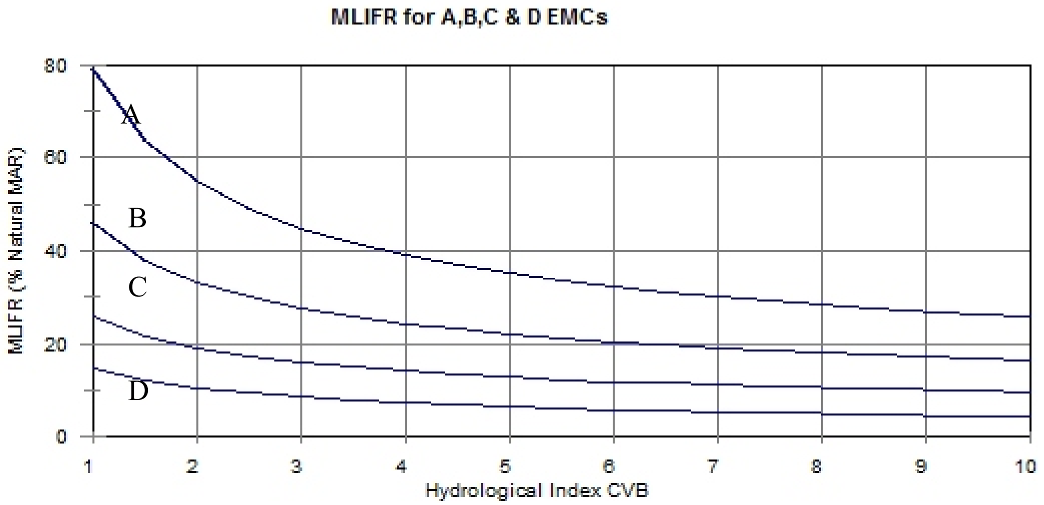


Figure 3.1 Maintenance low flow estimation curves over CVB index values 1.0 to 10.0 (the curves give progressively lower values for EMCs A to D)

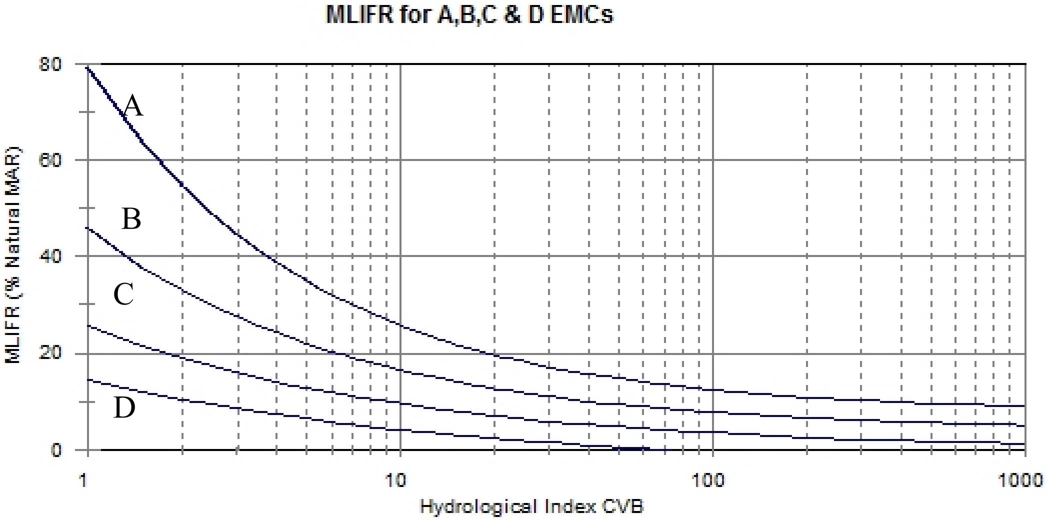


Figure 3.2 Maintenance low flow estimation curves over a wide range of CVB index values (the curves give progressively lower values for EMCs A to D)

Maintenance high flow values

It was found to be very difficult to construct estimation equations for the maintenance high flow requirements, largely because there seems to have been a greater degree of subjectivity and inconsistency in the setting of high flows in past IFR workshops than for the low flows. This is perhaps inevitable given the state of our understanding of the importance of channel forming discharges (related to magnitude-frequency relationships and geomorphological processes).

A graphical illustration of the currently used estimation equations for total maintenance requirements (i.e. MTIFR = MHIFR + MLIFR) is provided in figure 3.3 for the four main management classes over a CVB index range of 1.0 to 20.0. The actual estimation equations are given below and the parameter values for different EMCs are given in Table 3.10.

Estimation equation for MTIFR (maintenance total flow total as % natural MAR) :

If CVB < 2.0 then :

$$MTIFR = MLIFR + (TP1 * 2.0 + TP2 - LP4 + (LP1 * LP2) / (2.0^{LP3})^{(1 - LP1)} \quad \ldots\ldots\ldots\ldots \text{Eq. 3.8}$$

If 2.0 < CVB < 8.0 then :

$$MTIFR = TP1 * CVB + TP2 \quad \ldots\ldots\ldots\ldots \text{Eq. 3.9}$$

If CVB > 8.0 then :

$$MTIFR = TP1 * 8.0 + TP2 \quad \ldots\ldots\ldots\ldots \text{Eq.3.10}$$

Equation 3.10 and Figure 3.3 indicate that the total maintenance requirement remains constant at index values of 8 and above. This modification was made following two workshops on drier rivers with high index values (in the Northern Province and the Eastern Province) and is based on the assumption that they require quite large high flow contributions, but that these can occur with relatively low assurance. The low assurance means that the long-term mean requirement remains relatively low.

Table 3.10 Parameter values of the equation to estimate the annual total maintenance total (low plus high) flows.

Parameter	Ecological Management Class						
	A	A/B	B	B/C	C	C/D	D
TP1	-4.2	-3.6	-3.0	-2.5	-2.0	-1.7	-1.5
TP2	70	60	48	39	32	27	22

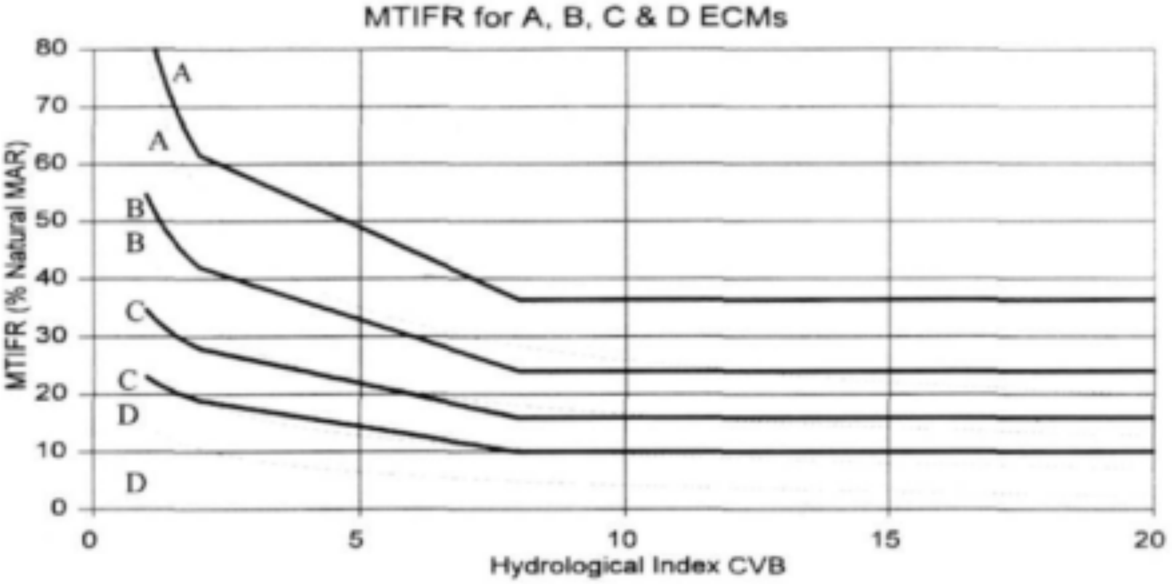


Figure 3.3 Maintenance total IFR requirements for EMCs A, B, C and D. The heavy lines are the total flow requirements, while the broken lines represent the low flow requirements given in Figures 3.1 and 3.2. Clearly the high flow requirements are the differences between the two sets of lines.

3.4.4 Drought IFR components

There were no discernable patterns or relationships between previous IFR results for either high or low flow drought requirements and any of the hydrological indices that were tested. Subsequently, it has been noted that it does not really make ecological sense to think in terms of varying the drought flow requirements with management class, as drought flows are considered to be the minimum required to prevent the system from collapsing. After some discussions amongst experienced IFR specialists ***it was decided that the drought low flow requirements (DLIFR) for all the management classes should be equivalent to the MLIFR for a 'D' EMC***. The implication is that if a D class is selected the river would experience drought conditions more or less permanently (although, in practice, the situation is slightly different and more water is required after the assurance rules are applied - see Section 3.6).

In terms of drought high flow requirements, no reasonable estimation approach could be developed and it was decided to handle these separately using the assurance rules (Section 3.6).

3.4.5 Parameter file for the DSS

All of the parameters required for the estimation procedures referred to above are contained within a parameter file (currently ***HYDRO.PAR***) which is used by both ***RESDSS*** and ***SARES*** to ensure that the application of the equations conform to the current form of the relationships without having to re-compile the programs. Table 3.11 lists the first part of the parameter file that deals with the calculations of the hydrological index and the annual IFR requirement values.

Table 3.11 First part of ***HYDRO.PAR*** containing the parameters of the annual IFR estimation equations (for EMCs A, A/B, B, B/C, C, C/D & D, in that order) and the parameters of the BFI estimation equation.

```
Parameters for hydro-IFR estimation
10
Parameter P1 in MIFR (%MAR) Equation for A to D classes
   0.90  0.905 0.91  0.915 0.92  0.925 0.93
Parameter P2 in MIFR (%MAR) Equation for A to D classes
  79    61    46    37    28    24    20
Parameter P3 in MIFR (%MAR) Equation for A to D classes
   6.0   5.9   5.8   5.6   5.4   5.25  5.1
Parameter P4 in MIFR (%MAR) Equation for A to D classes
   8     6     4     2     0    -2    -4
Parameter P1 in TIFR (%MAR) Equation for A to D classes
  -4.2  -3.6  -3.0  -2.5  -2.0  -1.75 -1.5
Parameter P2 in TIFR (%MAR) Equation for A to D classes
  70    60    48    39    32    27    22
Two thresholds for TIFR (%MAR) Equation
   2     8
Removed data
   0     0     0     0     0     0     0
Three parameters of the BFI estimate Eq. from Q75/ADf and T0
   0.832 0.272 0.006
Two parameters of the Q75/ADF estimate Eq. from Q75/MMF
   0.89 -0.0099
```

Both programs use a default version of this parameter file, which can be edited at any time by the user (under guidance by the developers). ***RESDSS*** includes an option to load a parameter file with an alternative name (i.e. several parameter files can be established and used as necessary). Further details of other information contained within the parameter files are given in Sections 3.5 and 3.6.

3.4.6 Using IFR workshop results

Should an IFR workshop have been held at the site (or close to the site) in question and the results are considered to be reliable, they can be used by ***RESDSS*** in place of the annual values generated by the generic relationships. This option (Get Obs. IFR Data) accesses a Paradox database table which includes location details, natural and present day MARs, as well as monthly volumes of IFRs for the maintenance and drought, low and high flow requirements. Importing these data override both the annual values estimated from the characteristics of the natural flow data time series as well as the regionalised monthly distributions discussed in the next section. The regional assurance rules are not replaced as many of the past IFR workshop results do not include information on the rules and they do not form part of the database.

The utility ***IFREDIT*** (provided with the DSS) enables new IFR workshop results to be added to the database or existing data to be edited to reflect revisions that might have been made since the original workshops.

3.5 Monthly distribution determination (*dated August 1999*)

The previous section addressed the issues relating to the estimation of the annual values of the IFR requirements, while this section outlines the procedures used to distribute these annual totals into monthly volumes. The addition of the option to use existing IFR workshop results (referred to in section 3.4.6) applies to this section as well. It should be pointed out that if this option is used before setting the region and management class, the region must still be specified before continuing with the assurance rules part of the program.

3.5.1 Monthly distributions of low flows (maintenance and drought)

The basis for the monthly distribution of low flows is the regional analysis of mean monthly baseflow contributions to total streamflow carried out by Cobbing (1998). This study investigated a number of observed daily flow records or simulated time series for South African rivers and carried out baseflow separation exercises on all of them, extracting monthly total and baseflow contributions. A regionalisation analysis then resulted in a number of 'generic' regional monthly distributions of baseflow proportion. Münster (1998) used these distributions in association with the actual monthly distributions of IFR low flows from past IFR results to determine a suitable estimation approach. ***One of the basic principles of the approach is that a higher proportion of the natural monthly flow is required during the dry months than during wet months.*** This principle appears to apply to both the higher and lower flows that occur as a result of seasonal changes, as well as the differences that occur as a result of periods of dry and wet years.

The actual estimation equation is based on one set of monthly parameters that represent the mean proportion of total flow (**PAR1**$_i$ for i = 1 to 12) for each month of the year that can be expected to occur as baseflows (based on a hydrological definition). Two additional parameters (**PAR2** and **PAR3**) define the extent to which the natural range of monthly baseflows will be reduced (or increased) in the monthly distribution of maintenance and drought flows (i.e. one parameter for maintenance and one for drought). The maintenance parameter is the value used for an 'A' EMC, while for the classes between 'A' and 'D' (drought flows) linear interpolation is used between the two values. The parameter file (***HYDRO.PAR*** by default) includes values for 20 defined regions of the country. These 20 regions have been identified on the basis of their broad similarity of seasonal distributions of runoff response, as well as their characteristics of flow variability, which is more important for setting the assurance rules discussed in Section 3.6. Table 3.12 provides the values for the monthly distributions of all the 6 parameters for each of the 20 regions.

The range reduction value is estimated from :

$$FDIST = PAR2 - (PAR2 - PAR3) * EMC/6 \quad \text{.................................... Eq. 3.11}$$

where EMC is the management class value (0 = A, 1 = A/B, to 6 = D)

The baseflow monthly distribution is calculated from :

$$QBASE_i = QTOT_{i\,*}\, PAR1_i \quad \text{.. Eq. 3.12}$$

where QTOT$_i$ are the mean monthly natural flow volumes for months i and QBMIN is then set as the minimum of the QBASE$_i$ values.

The first estimates of the distributions of monthly IFR flows are calculated from :

for maintenance :

$$Q1_i = QBMIN + (QBASE_i - QBMIN) * FDIST \qquad \text{Eq. 3.13}$$

for drought :

$$Q2_i = QBMIN + (QBASE_i - QBMIN) * PAR3 \qquad \text{Eq. 3.14}$$

these values are then summed (QTOT1 and QTOT2)

The monthly maintenance values are then given by :

$$QM_i = Q1_i * MLIFR / QTOT1 \qquad \text{Eq. 3.15}$$

And the monthly drought values by :

$$QD_i = Q2_i * DLIFR / QTOT2 \qquad \text{Eq. 3.16}$$

The values of **PAR2** are always greater than the values of **PAR3**, and both are less than 1.0, suggesting that the distribution of droughts is relatively flatter than maintenance flows and that they are both flatter than the natural seasonal distribution. This is consistent with the concept of 'giving away' relatively more water during the wet season than the dry season. The values of **FDIST** and **PAR3** are displayed on the screen within ***RESDSS*** and can be edited to allow the seasonal distributions of maintenance and drought flows to be modified.

The region names given in Table 3.12 can be very confusing because some of the regions were named after their core area, but the same distributions were then applied to more extensive areas. An Arc View coverage is available (and supplied with the software) which illustrates the regional distribution and allows the default region used for each quaternary catchment to be identified. Within ***SARES,*** the database table ***WR90*** is accessed and this contains a field which identifies the default region for each quaternary by number. ***The 'Region' field in the database table WR90RES contains the region number relevant to the accumulated flow time series that has been derived after MAR weighting of the region numbers for the upstream incremental quaternary catchments.***

Within ***SARES*** the monthly distributions associated with the number of the region in the database are used automatically for the estimates. Within ***RESDSS,*** the user first sets the EMC and then manually selects the region to be used. Thereafter, the seasonal distributions are calculated and displayed (as either %MAR, $m^3 * 10^6$ of volume, or $m^3\ s^{-1}$ of mean monthly flow units).

3.5.2 Monthly distributions of high flows

Table 3.12 also includes a parameter line for the maintenance high flow distributions and these values are used with the baseflow proportions in the following manner :

For all months (i = 1 to 12) the annual total (HT) of natural high flows is calculated :

$$HT = \sum (Total\ flows_i - Baseflows_i) \qquad \text{Eq. 3.17}$$

For each month the natural high flows (H_i) are expressed as a % of the total (HT) :

$$H_i = (Total\ flows_i - Baseflows_i) * 100 / HT \qquad \text{Eq. 3.18}$$

The non-dimensional high flows (HND_i) for all months not having -9 parameter values and the balance of the total high flow volume remaining (REM) to be distributed are calculated :

$$HND_i = parameter_i * H_i \qquad \text{Eq. 3.19}$$

$$REM = 100 - \sum HND_i \qquad \text{Eq. 3.20}$$

The sum and maximum values of the H_i values for those months with -9 parameters are calculated and the non-dimensional high flow value for the month with the maximum set to the square root of the maximum divided by the sum multiplied by REM :

for only those months with -9 parameters :

$$HND_i\ (at\ maximum\ H_i) = REM * SQRT(Max(H_i) / \sum H_i) \qquad \text{Eq. 3.21}$$

The remaining months with -9 parameters are then estimated from the balance depending on their proximity (in months) to the maximum month and the total number of months with -9 parameters. The final step is to dimensionalise the values using the annual total high flow IFR value :

$$HIFR_i = HND_i * (MTIFR - MLIFR) / 100 \qquad \text{Eq. 3.22}$$

Table 3.12 Regional parameter values for the monthly distributions of annual values, as well as the assurance rules (Section 3.6)

```
Number of regional baseflow distributions (%MMR)
20
dataline 1: Baseflow proportions (% Total monthly flow)
dataline 2: MLIFR and DLIFR Distribution parameters 1 and 2
dataline 3: High flow distribution factors
dataline 4: Summer (Jan) default rule parameters
dataline 5: Winter (Jul) default rule parameters
1. W.Cape(wet)
70.0  62.0  40.0  37.0  35.0  32.0  25.0  20.0  25.0  36.0  42.0  52.0
0.9 0.65
1.0 0.0 0.0 0.0 0.0 0.0 0.0 1.0 1.0 -9.0 -9.0 -9.0
6.0 98.0 20.0 120.0 6.0
4.0 98.0 20.0 120.0 4.0
2. W.Cape(dry)
65.0  64.0  36.0  10.0  10.0  10.0  12.0  13.0  18.0  24.0  34.0  42.0
0.8 0.55
1.0 0.0 0.0 0.0 0.0 0.0 0.0 1.0 1.0 -9.0 -9.0 -9.0
7.0 100.0 10.0 130.0 7.0
7.0 100.0 10.0 130.0 7.0
3. W.Karoo
30.0  20.0  18.0  12.0  8.0  10.0  15.0  30.0  38.0  40.0  42.0  40.0
0.80 0.55
1.0 0.0 0.0 0.0 0.0 0.0 1.0 -9.0 -9.0 -9.0 1.0 1.0
25.0 65.0 0.0 200.0 25.0
12.0 80.0 0.0 200.0 12.0
4. E.Karoo
20.0  26.0  22.0  22.0  20.0  20.0  20.0  25.0  25.0  25.0  22.0  20.0
0.80 0.55
0.0 1.0 1.0 1.0 -9.0 -9.0 -9.0 1.0 1.0 1.0 1.0 0.0
15.0 75.0 0.0 200.0 15.0
20.0 70.0 0.0 200.0 20.0
5. S.Cape(dry)
28.0  26.0  22.0  20.0  18.0  19.0  20.0  30.0  28.0  29.0  31.0  29.0
0.80 0.55
-9.0 1.0 0.0 0.0 0.0 0.0 1.0 1.0 0.5 0.5 -9.0 -9.0
12.0 100.0 10.0 130.0 12.0
8.0 100.0 10.0 130.0 8.0
6. S.Karoo
30.0  20.0  18.0  12.0  8.0  10.0  15.0  30.0  38.0  40.0  42.0  40.0
0.80 0.55
-9.0 1.0 0.0 0.0 0.0 0.0 1.0 1.0 0.5 0.5 -9.0 -9.0
14.0 100.0 10.0 150.0 14.0
10.0 100.0 10.0 150.0 10.0
7. S.Cape(wet)
35.4  34.6  45.3  53.6  32.7  39.2  35.1  42.9  41.9  31.6  31.4  35.2
0.85 0.65
-9.0 -9.0 0.0 0.0 0.0 -9.0 1.0 1.0 0.0 0.0 1.0 1.0
8.0 100.0 10.0 130.0 8.0
6.0 100.0 20.0 120.0 6.0
8. E.Cape(arid)
16.0  16.0  16.0  16.0  16.0  16.0  16.0  16.0 16.0 16.0  16.0  16.0
0.80 0.55
-9.0 -9.0 1.0 0.0 0.0 -9.0 1.0 0.0 0.0 0.0 1.0 -9.0
15.0  85.0 0.0 200.0 15.0
20.0  75.0 0.0 200.0 20.0
9. E.Cape
19.0  27.0  27.0  21.0  20.0  13.0  18.0  40.0  40.0  35.0  30.0  22.0
0.75 0.55
1.0 -9.0 -9.0 0.5 0.8 -9.0 1.0 0.0 0.0 0.0 0.0 1.0
8.0 90.0 0.0 130.0 8.0
10.0 95.0 0.0 130.0 10.0
```

An example is provided in Table 3.13 for the D'Berg (13) region using quaternary catchment D16D. The first column provides the mean monthly distribution volume of the assumed high flow contribution based on mean monthly flow * (1 - baseflow proportion). The second column recalculates the first column values as a % of the total high flow contribution. The third column lists the parameter values for this region, while the fourth column lists the non-dimensional requirements for the months that have positive parameter values. Column 5 identifies the peak high flow requirement month and lists the non-dimensional requirement using Eq. 3.15, while column 6 gives the distribution parameters for the remaining -9 months and column 7 their non-dimensional requirements. The values in columns 4, 5 and 7 can then be dimensionalised by the annual high flow requirement. Note the pattern of distribution parameters given in column 6 and the fact that one of the remaining months has double the requirement of the other two and that it is the furthest away from the month with the maximum requirement.

Table 3.13 Monthly high flow distribution example using quaternary D16D in the Drakensberg region (Note that the sum of columns 5, 6 and 8 must equal 100).

Month	Total - Baseflow ($m^3 * 10^6$)	H_i %	Parameter	HND (non -9's)	Max of -9's	Factors for other -9's	HND (other -9's)
Oct	4.1	7.7	0.5	3.85	-	-	-
Nov	6.7	12.5	1	12.5	-	-	-
Dec	6.9	12.9	-9	-	-	0.5	18.09
Jan	10.3	19.2	-9	-	-	0.25	9.05
Feb	11	20.6	-9	-	43.85	-	-
Mar	8.5	15.9	-9	-	-	0.25	9.05
Apr	2.4	4.5	0.8	3.6	-	-	
May	0.5	0.9	0	0	-	-	
Jun	0.3	0.6	0	0	-	-	
Jul	0.2	0.4	0	0	-	-	
Aug	0.4	0.7	0	0	-	-	
Sep	2.2	4.1	0	0	-	-	
Total	53.5	100	N/A	19.95	43.85	N/A	36.2

3.5.3 Manual adjustment of monthly values

This option is only available within ***RESDSS*** and both the monthly distributions of low flows and the annual values can be changed (but not the distribution of high flows, except by editing the parameter data). Once all the distribution data are displayed on the screen, the user has the option to increase or decrease the drought low flow, maintenance low flow and/or the maintenance total flow annual values. The monthly distributions are then re-calculated using the methods described in this section.

3.6 Establishing the assurance rules *(dated March 1999)*

The table of monthly volumes generated after the annual values have been calculated and the monthly distributions applied are essentially equivalent to the output (in terms of monthly volume requirements) from IFR workshops where the traditional approach to the BBM was applied. The only real difference is that no values are provided for drought high-flow requirements and no details are given for the peaks and durations of the individual high-flow events required. The latter detail is inappropriate to a method based on a monthly time step.

Recent IFR workshops have commonly taken the process one step further and provided guidelines on the time series patterns of requirements. They have also specified in more detail under what circumstances and how frequently, different flows (i.e. maintenance or above, between maintenance and drought, or at drought) should occur in the modified time series. This has usually been carried out through the application of the so-called ‘IFR Model’ (Hughes, et al., 1997). The model generates a modified time series of flow requirements that can be assessed and revised by the workshop participants through a calibration process. One of the possible outputs from the model is an analysis of the % of time that the recommended flows are equaled or exceeded (i.e. a flow duration curve analysis), which can also be thought of as expressions of the assurance whereby certain target flows are achieved. ***This information is required by the Water Resource Engineers for planning and management purposes and is equivalent to the normal expressions of assurance that are used to quantify the reliability of a component of a water supply project.***

In developing the structure of the DSS for the planning estimate it was decided to make use of the same concept, but perform the analysis in reverse; that is define the ‘rules’ for assurance and then use these to generate a representative time series of required flows.

3.6.1 Generic assurance rules and assurance curves

Generic regional assurance curve parameters have been included in the parameter file shown in Table 3.12 and Figure 3.4 illustrates two possible curve shapes. The x-axis of the curves represents the frequency with which flows specified on the y-axis are expected to be equaled or exceeded in a representative time series of modified flows (and is therefore also the assurance with which such target flows are expected to be met). Within ***RESDSS*** two curves are graphically displayed: one representing the low-flow component and one the total-flow component. The non-dimensional shape of the curves is defined by four basic parameters and then parameterised by the maintenance and drought-flow requirements.

The four parameters are as follows :

Shape factor (1 to 25) :

In Figure 3.4 the values used are 5 for Regions 13 and 15 for Region 4. A higher shape factor generates a curve that moves down from higher flows to lower flows at a relatively low assurance value. A low shape factor generates a curve which remains at high flows until quite high assurance values.

Upper time shift (65 to 100) :

In Figure 3.4 the values used are 98 for Regions 13 and 75 for Region 4. This parameter represents the lateral shift (toward the left, or low assurance end) of the lowest point (drought flow) of the assurance curve.

If the upper time shift parameter is decreased this will effectively increase the duration that flows within the modified flow regime which will be at the specified drought level.

Lower time shift (0 to 50) :

In Figure 3.4 the values used are 20 for Region 13 and 0 for Region 4. This parameter represents the lateral shift (toward the right, or higher assurance end) of the maximum point (at or above maintenance flow) of the assurance curve. If the lower time shift parameter is increased this will increase the duration that flows within the modified flow regime will be at the maximum value.

Low flow maximum (100 to 200) :

In figure 3.4 the values used are 120 for Region 13 and 200 for Region 4. One of the principles of the BBM is that the specified maintenance flows are not considered to be the maximum that would be expected. This parameter therefore represents the maximum low flow that is required and is a % of the monthly maintenance low flow requirement.

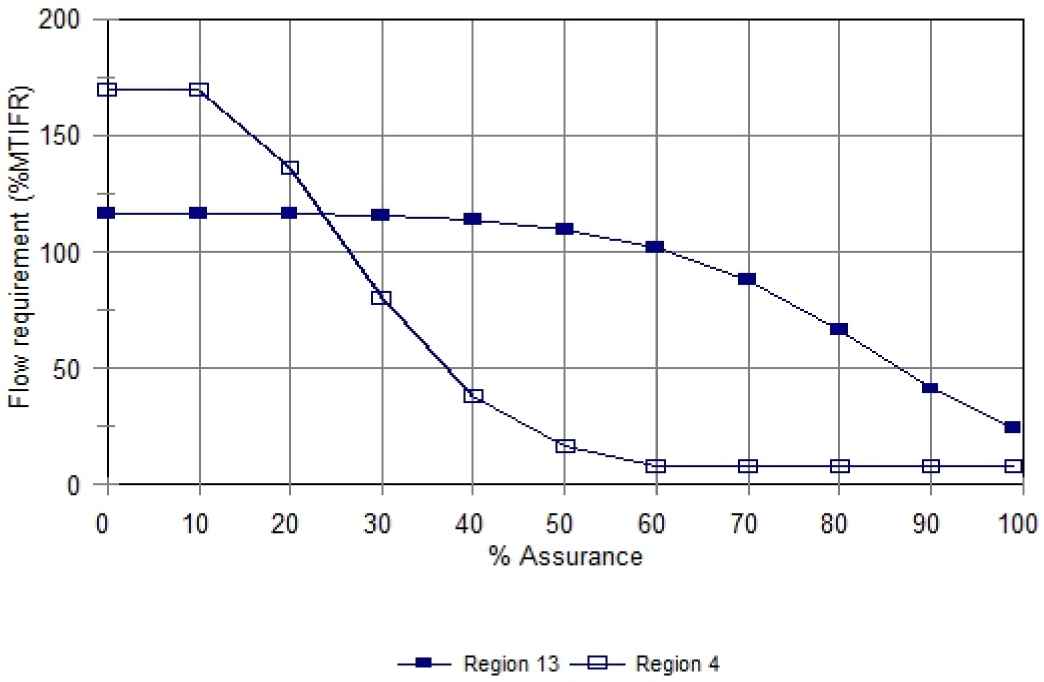


Figure 3.4 Examples of generic assurance rule curves for the month of January for region 13 (D'Berg) and region 4 (E. Karoo)

The first four values of the first line of assurance parameters given in Table 3.12 are for the low flow curve for January, while the last value is the shape parameter for the high flows (at present this is always the same as the low flow shape parameter). The second line of assurance parameters is for the month of July, while the parameters for the other months are determined by interpolation between January and July.

The ***low-flow rule curve*** is finally quantified using the maintenance low-flow requirement (Section 3.5.1) scaled up by the low-flow maximum parameter to represent the highest flow and the drought low-flow requirement to represent the lowest flow.

The ***total flow rule curve*** is quantified by adding a high flow curve to the low flow rule curve. The high flow curve is quantified in the following way :

The shape factor is a specified parameter.
The upper and lower time shifts used are the same as for the low flow curve.

The maximum value is calculated from (i = months 1 to 12) :

$$HIFR_i * (1.0 + (\text{Low flow max. parameter} - 100)/200) \qquad \text{Eq. 3.23}$$

The minimum, or drought high flow requirement is calculated from :

$$HIFR_i * 0.1 \qquad \text{Eq. 3.24}$$

These generic regional rules have been established on the basis of a number of principles that have emerged out of various discussions with ecologists and other IFR specialists. ***However, there is still a great deal of scope for further debate, particularly around those rules used within the drier catchments of the country where there is no existing experience base of setting environmental flow requirements.*** The general principles are listed below to provide a basis for constructive debate and further refinement of the rules.

- ☐ The ***shape factor*** and ***lower time shift*** parameters have been set to result in a relatively high assurance of maintenance flows for natural flow regimes with high baseflow contributions and low variability. This principle has already been established at several IFR workshops. The assurance of maintenance is expected to decrease as the flow regime becomes more variable.
- ☐ Coupled to the lower assurance of maintenance for rivers with more variable flow regimes, is the requirement to allow the ***maximum low flow*** to exceed the specified maintenance flow by a relatively greater amount. This will introduce a relatively high degree of variability into the modified regime to be consistent with the characteristics of the natural regime.
- ☐ The procedure for setting the maximum value for the high flow requirement follows the same principles as that of low flow maximum. However, the conceptual basis for applying this procedure to high flows is less well-developed than for low flows.
- ☐ Setting the drought high-flow requirement to 10% of the maintenance requirement is a pragmatic (and fairly conservative) approach to a problem that exists because of the lack of any information.

Within SARES the rule tables (one for each calendar month) are written to BLOB fields within the ***WR90RES*** database for later access.

3.6.2 Additional high flows at low assurance

During two workshops held in July/August 1999 to look at the use of the model in drier rivers with variable regimes (the example rivers were located in the Northern and Eastern Provinces), it was noted that the model does not allow for the higher flow events that are frequently set during Reserve determinations with return periods that are greater than the equivalent of the maintenance assurance level (e.g. 1:3 to 1:5 year events).

The workshop participants noted that these events might assume a very important role in the drier and more variable flow regimes, because the other flows which are set have low assurance levels and are usually quite small. The changes in the approach to setting the high flow requirement for relatively high index values have already been outlined in previous sections and this accounts, to a certain extent, for the comments that were made during the workshops.

The refined approach is only applied to those months which have a -9 value for the maintenance high flow distribution (see section 3.5.2) and affects different parts of the total assurance curve depending upon the value of the shape factor. Figure 3.5 shows a plot of the shape parameter versus the 'Critical % Assurance' (the bold line and left-hand vertical axis). The 'Critical % Assurance' represents the maximum assurance value at which high flows are affected by this modification and is calculated from:

$$\textit{Critical \% Assurance} = 59.8 - \textit{Shape Factor} * 1.95 \quad \text{..... Eq. 3.25}$$

This equation was derived on the basis of always having at least the 10% assurance value affected and the 50% value affected for the rivers with the least variable flow regimes (currently a shape factor of 5).

The second component of the modification is to specify the size of the increased high flows and that is illustrated by the thin line and the right-hand vertical axis in Figure 3.5. First of all, for the major flood months (-9 distribution parameter) the maximum value of the initial high flow assurance curve is set to $\mathbf{HIFR_i}$ and not the value given by Equation 3.25. The following algorithm is then used to estimate the additional high flows :

$$HIFR_i * (\textit{Shape Factor} / 4) * \{(100 - \%\ \textit{Assurance}) /100\}^{Power} \quad \text{..... Eq. 3.26}$$

Where

$$\textit{Power} = (\textit{Shape Factor})^{0.6} \quad \text{..... Eq. 3.27}$$

The value for additional high flows increases from the Critical % Assurance to a maximum value at an assurance of 10% and then remains constant. Figure 3.5 provides a graphical illustration of the variation in maximum additional high flows (as a multiplier of $HIFR_i$) with the shape parameter. If the shape parameter has a value of 5 (Eastern Escarpment rivers, for example), the additional high flows start having an influence at an assurance value of 50%, where 20% of the maintenance high flow value is added. At 30% assurance, 49% of HIFR is added, while the maximum additional value is 95% HIFR. In contrast, for the Eastern Karoo region with a shape parameter of 15 the influence begins at 30% assurance, with 46% of HIFR added and the maximum added is 202% of HIFR. It should be clear that one of the assumptions made is that the ratio of extreme event volumes to maintenance event volumes will increase as the hydrological regime becomes more variable (as reflected by higher shape factors).

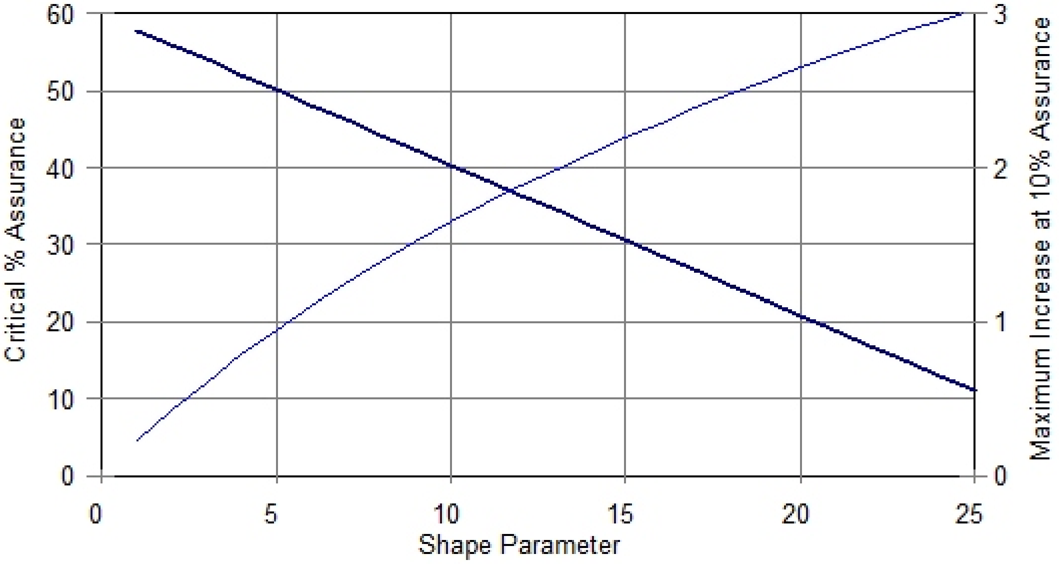


Figure 3.5 Illustration of the variation in Critical % Assurance and the maximum value (relative to maintenance high flow requirement) of the added high flows for different shape parameters.

3.6.3 User intervention in the assurance rules

The only form of user intervention in the rules within ***SARES*** is by editing the parameter file for a specific region and re-generating the rules and the modified flow-time series. The same intervention also clearly applies to ***RESDSS***.

Additional user control of the rules is incorporated into ***RESDSS***. The window that displays the rules graphically, includes an option to toggle between the months of the year and to modify the five parameters that are applicable to each month. These five parameters are the low and high flow shape factors, the lower and upper time shifts and the low-flow maximum value. As these are changed, the graphical representation of the rule curves are changed as well, and these can be compared with the shape of the natural flow duration curve for that specific month.

3.6.4 Use of the assurance rules to generate modified time series

The final stage of the time series processing for both programs is to generate a modified time series of the same length as the natural time series referred to in Section 3. This is carried out by using the calendar month duration curves of the natural time series and the assurance rule curves referred to above. The programs step through the natural time series, identifying the duration curve percentage point value of each month and generating the modified (IFR) flow as the monthly discharge volume equivalent to the same percentage point on the assurance curve for the same calendar month.

Within ***RESDSS*** the new time-series data are plotted together with the natural values and can then be saved to file.

Within ***SARES,*** the low-flow and the high-flow contributions to the total modified flow are written to BLOB (Binary Large Object) fields within the **WR90RES** database table. They can then be written to text files at a later stage.

3.7 Results summary and output data generation (*dated August 1999*)

Some comments about the various facilities for generating output data have already been referred to in previous sections. This section is designed to provide an overall summary of the information that can be viewed or extracted from the two programs.

3.7.1 Program *RESDSS*

Because ***RESDSS*** is designed for site-specific applications of the techniques, there are more facilities for visualizing the results at various stages in the estimation process.

Natural time-series generation:

At this stage, a table of annual (mean, standard deviation, CV, Q75) and monthly statistics (means, standard deviations, CVs) is provided, as well as a facility to save the total time series (i.e. accumulation of all the selected quaternary data) as a text file in WR90 format.

EMC and present status scores:

These can be saved to a file for later retrieval and editing.

Annual and monthly IFR values:

These occur simultaneously within the program after the management class and regional type have been selected. A detailed summary of the statistics of the natural time series, as well as the annual and monthly IFR values can then be printed. The printout specifies which quaternaries have been used, the management class selected and the generic regional distribution type. A further option allows the monthly distributions of total natural flow, separated natural baseflows and the three main IFR components (maintenance low and total flows, drought low flows) to be graphically displayed using either a log or linear axis.

Setting the assurance rules:

At this stage in the program the only output options are to print the assurance rule table or write it to a text file with a default extension of ***.rul**. The data can be output as mean monthly discharges in $m^3 s^{-1}$, or as monthly flow volumes in $m^3 * 10^6$, for 10 percentage points (10, 20, 30, 40, 50, 60, 70, 80, 90, 99%) for each month of the year.

Generating the modified time series:

This section of the program graphically displays the natural and modified time series in a way which allows the user to zoom in and out on specific parts of the series and display the flow axis as linear or log values. Part of the screen display includes the mean annual volume, in $m^3 * 10^6$ and % natural MAR, of the modified flows. There are also options to save either the total modified time series or the remainder flows (natural flows - IFR) to a WR90 format text file.

Determining an estimate of the reduction in yield :

This option allows the user to load up a text data file of the parameters of the relationships between yield and storage which are based on the diagrams provided in WR90. The shapes of these curves had previously been generalized by van Rooyen and de Jager (1998) into 3 parameters of non-linear equations expressing yield (as % natural MAR) as a function of storage (also as % natural MAR) for various return periods and for each hydrological zone. These parameters have been updated recently for the purpose of populating the database of the National Water Balance Model and have been calculated for every quaternary catchment on the basis of the cumulative runoff regime at the outlet of the quaternary. The difficulty with the old approach was that the equations could not easily be combined where upstream quaternaries crossed several hydrological zone boundaries. This difficulty had now been overcome. The form of the equation used is:

$$\textit{Yield} = A\,(\textit{Storage})^{B} + C \quad \text{Eq. 3.28}$$

The procedure adopted is that the parameters have already been added to the main WR90 database table, such that the quaternary name is used as a lookup key to extract the correct values. The user can set the required storage (as %MAR from 0 to 400 in increments of 5%) as well as the return period (10, 20, 50 or 100). The required storage is used to estimate the equivalent yield value (Y in % MAR year^{-1}) and the critical length (in years) of the drought period that determines the yield is then estimated from the inverse of the derivative of equation 3.28 :

$$dY/dS = A\,B\,S^{(B-1)} \quad \text{Eq. 3.29}$$

Where dY/dS is the inverse of the slope of the storage-yield relationship at S and is therefore a length of time in years. This duration is then used with the time series of Ecological Reserve requirements to find the minimum requirement (by comparing all possible running sums) over that critical duration. The minimum requirement is then reduced to an annual equivalent (dividing by the period) and expressed as a percentage of the natural mean annual runoff for the site. This value can be considered to be an estimate of the reduction in yield that can be expected if the estimated reserve requirements are met and is not considered part of the exploitable component of the natural flow regime. If a zero storage is selected, the critical duration is taken to be 3 months.

Some comparisons have been made with the results of applying the residual flow (natural flows less reserve requirements) time series with a monthly reservoir simulation program.. The yield reductions given by the two methods are broadly comparable.

The yield derived from Equation 3.28 (i.e. based on the total natural flows with no allowance for the Reserve) is also printed to the screen for comparison purposes and to put the reduction value into context.

3.7.2 Program *SARES*

For this program the annual values for both the natural flows and the IFR modified flows are provided in the database table, while the detail (monthly distributions, assurance rules and modified time series) are stored in BLOB (Binary Large Objects) fields. The main summary facilities are therefore designed to allow the data in these BLOBs to be displayed or sent as an output to file.

Monthly distribution of IFR:

These data can be listed on the screen for a specific quaternary catchment outlet once a database record has been selected (click on the required record in the table).

Assurance rules:

The assurance rules can be saved to a text file in the same way, and using the same format as in ***RESDSS.***

IFR modified time series:

There are three options for saving IFR modified time series data to text files (WR90 format): the user chooses between saving only the low-flow, or only the high-flow components, or the total IFR.

Output of WR90 or WR90RES field data as text files:

There are several options to output the quaternary catchment names together with some of the database field data as text files. Examples include the region number, information on the baseflow contribution of quaternary catchments and the CVB index values.

Yield reduction estimates:

The method of estimating the mean annual water supply yield reduction consequent upon the implementation of the IFR modified flow time series as the Reserve (see section 3.7.1) has been added to ***SARES*** in the form of an output table of yield reduction factors for several storage values (0, 10, 25, 50, 100, 200, 400, 1000% MAR), given a 1:50 year drought and for EMCs A, B, C and D (as well as for A200 = 100% MAR requirement and D0 = 0% MAR requirement). At present, yield reductions under different management classes for run-of-river abstractions (0 storage) are based on a critical drought duration of 3 months instead of the value given by Equation 3.29.

3.7.3 Proposed future options

There are several options that are planned to be included within the programs in the near future.

Use of MapObjects (or similar) to access Arc View coverages and select catchment areas or regional parameter data directly :

At present the ArcView coverages of various items of spatial information can be distributed with the software, and an option is included to display these as bitmap images. However, it is also planned to make use of a spatial coverage analysis option that is available for DELPHI (such as MapObjects). This type of software allows the spatial coverages (and associated relational databases) to be accessed and analyzed within a DELPHI program. While the required software is somewhat expensive at present, its use would extend the functionality of the various programs and will certainly be considered in the future.

Incorporation of modifications to the annual estimates and the seasonal distributions based on physical and biological factors :

Münster and Hughes (1999) and section 4 of this report describe an approach for using information on the physical and biological characteristics of river cross-sections to estimate correction factors to some of the

IFR values derived by ***RESDSS***. At present these procedures have been incorporated into a separate program (***ECSCORE***) that allows scores to be estimated for annual maintenance and drought low-flow requirement totals, distributions of low flows and annual high-flow requirement totals. The concept is that these scores will then be used to adjust the purely hydrological estimates that are given by ***RESDSS*** once comment has been received by the broader 'Reserve' community.

4. POTENTIAL FOR THE INCLUSION OF PHYSICAL AND BIOLOGICAL FACTORS INTO THE RESERVE DECISION SUPPORT SYSTEM

This is an ongoing project and this section is merely a summary of findings so far. It should be seen as a discussion document and comments can be addressed to denis@iwr.ru.ac.za. This document has been compiled following discussions with the groups and individuals, listed below, who have in some way been involved in the IFR and Ecological Reserve process. Their input is gratefully acknowledged although no direct reference will be made to individual views and comments in the text.

The concepts and conclusions reached within this section of the report are based on a synthesis of the expert opinion of the specialists listed below and not on any documented relationships between hydrological, hydraulic and biotic regimes. The reasons for adopting this approach are related to the lack of such information except at a limited number of specific sites. The whole purpose of this part of the project was to look for generic concepts that could be applied over broad geographic areas.

- ***Institute for Water Research*** (Rhodes University) : Denis Hughes, Jay O'Keeffe, Tally Palmer, Dez Weeks
- ***Albany Museum*** (Grahamstown) : Jim Cambray, Ferdi De Moor
- ***Geography Department*** (Rhodes University): Evan Dollar,Marinda Du Plessis, Gillian McGregor, Kate Rowntree
- ***JLB Smith Institute*** (Grahamstown) : Roger Bills
- ***Southern Waters/Freshwater Research Unit*** (University of Cape Town) : Kate Brown, Helen Dallas, Jenny Day, Jackie King, Rebecca Tharme
- ***Statistical Sciences Department*** (University of Cape Town) : Allison Joubert
- ***Institute for Water Quality Studies*** (Department of Water Affairs & Forestry) : Liesl Hill, Sebastian Jooste, Neels Kleynhans, Heather MacKay, Christa Thirion
- ***IWRE*** (Pretoria) : Nigel Kemper, Delana Louw
- ***Afridev*** : Mark Chutter
- ***Streamflow Solutions*** : Andrew Birkhead
- ***CSIR*** : Nico Rossouw
- ***Umgeni Water*** : Chris Dickens
- ***Natal Parks Board*** : Mike Coke
- ***School of Bioresources Engineering and Environmental Hydrology*** (University of Natal) : Graham Jewitt
- ***Centre for Water in the Environment*** (University of the Witwatersrand) : Kevin Rogers

The computer-based decision support system (RESDSS) that has been developed within the Institute for Water Research to provide a "desktop estimate"is outlined in the previous section. As hydrological differences among rivers are more easily quantified than physical or biological differences, relationships between the hydrological characteristics of rivers and their IFRs are more "easily" identified. Thus hydrology thus, forms the core component of the DSS. As such, there is an underlying assumption in the method that the hydrological character of a river is one of the primary determinants of IFRs. This does seem reasonable considering that flow is the driving force of the aquatic ecosystem. However, instream flow requirements are considered to be influenced by two other variables: the physical and biological characteristics of the site/river/catchment; and the site-specific management objective. Incorporating some of these physical and biological aspects into the current DSS would almost certainly improve the accuracy of IFR estimations.

The aim of this sub-project was therefore to:

☐ Identify which generic factors potentially influence the total low-low and high-low instream flow requirements in South African rivers.

☐ Identify which generic factors potentially influence the seasonal distribution of low flows.

☐ Provide possible explanations why these factors influence the IFR.

☐ Establish, as far as possible, the relative/hierarchical importance of these factors.

☐ Quantify how these factors influence the IFR.

☐ Develop a practical method for establishing differences in IFRs.

4.1 Constraints of using physical and biological data in the DSS

The requirement for reserve desktop and rapid determination estimates to be rapidly quantifiable constrains the choice of variables used in any estimation procedure to be those for which data are readily available or obtainable for any river in any quaternary catchment in South Africa. Ideally, these data would be accessible from a national database. Alternatively, information should be able to be derived from some readily measured surrogate variables (such as slope, vegetation type, geology) through regional relationships.

Unfortunately, this kind of general countrywide physical and biological information either does not currently exist, or relationships between measurable surrogate variables and the actual characteristics relevant to instream flow assessment are still largely tentative and developmental in nature. Unlike hydrological data, which are available for all quaternary catchments from the WR90 database, and for which standard techniques exist for extrapolating information to sites or areas where data are scarce, physical or biological data for river ecosystems are largely limited to a few well-studied perennial rivers occurring mainly in the Lowveld, Eastern Upland and Southern Coastal Belt regions (regions as defined by Kleynhans & Hill, 1998). The complex interactions and multiple variables which contribute to the definition of the specific biological make-up of any particular site or river makes it much more difficult to extrapolate relationships and information to rivers and regions that have not been studied in detail, and to intermittent (seasonally flowing and truly ephemeral) river systems. This factor largely constrains the regionalisation, or generalisation, of biological aspects. It is, however, expected that physical characteristics may possibly be more easily and rapidly regionalised, or that easily measured surrogate variables can be used to describe the physical character of a site (eg. slope measured from a 1:50 000 topographic map may give an indication of geomorphological reach type (Rowntree et al., 1998). The current lack of a comprehensive countrywide database containing the ecological data relevant to instream flow assessment obviously poses the largest obstacle to incorporating physical or biological aspects into the DSS. At this stage collection of ecological information will therefore still require some form of "field work" (either site visits or video footage). This makes it impossible to incorporate an ecological component into the national desktop estimate (***SARES***). The potential value of such an ecological component will therefore be applicable only to site-specific estimates and will thus only be built into the ***RESDSS*** program.

A constraint of a more practical nature is that of the lack of clearly and unambiguously defined, ecologically relevant categories within each physical or biological variable. For example, no clear categories exist for different catchment sediment yields and, therefore, the distinction between catchments which have "high" or "low" sediment yields remains open to individual interpretation. Until this problem is addressed, any attempt to describe catchments and rivers on the basis of their physical and biological characteristics will remain highly subjective.

It is hoped that with time, and as increasing information becomes available for rivers in less comprehensively studied parts of South Africa, these practical hurdles will steadily be overcome.

4.2 Motivation for including an ecological component into the DSS

The general form of the relationship between the annual flow requirement and the natural hydrology is indicated by Figure 4.1. The symbols represent the relationships between the annual flow requirement (as set at past IFR workshops) and the hydrological index value for 13 IFR sites which had a "B" Ecological Management Class recommended. This plot reveals the general trend that, for the same

management class, flow requirements decrease as the natural flow regime becomes increasingly variable and event-driven. While the particular example used in Figure 4.1 is based on the maintenance low-flow requirements of B-class rivers, the general principle and results are similar for drought low-flows and maintenance high-flows, as well as for any other management class.

The trends found by plotting available IFR results against the "hydrological signal" of the sites have resulted in the construction of a series of "best-fit" curves for each of the different management classes and IFR components. In Figure 4.1 this curve is indicated by the bold centre line. These curves form the basis of the DSS as they are used to estimate annual flow requirements once the hydrological index value has been calculated and the management class of the site or catchment is known.

From Figure 4.1 it is evident that past IFR results are scattered within a range of approximately 20% above or below the estimated flow requirement. While some of this "noise" may be attributed to the inaccuracies and subjectivity inherent in the Building Block Methodology, this explanation for the variability can not effectively be taken account of in any way. However, it is the contention of this document that at least some of this scatter is related to the physical and biological differences between
sites (the "ecological signal"). It is expected that by quantifying the effect of these ecological signals, and using this in combination with the hydrological signals to estimate flow requirements, it would reduce this current level of "noise".

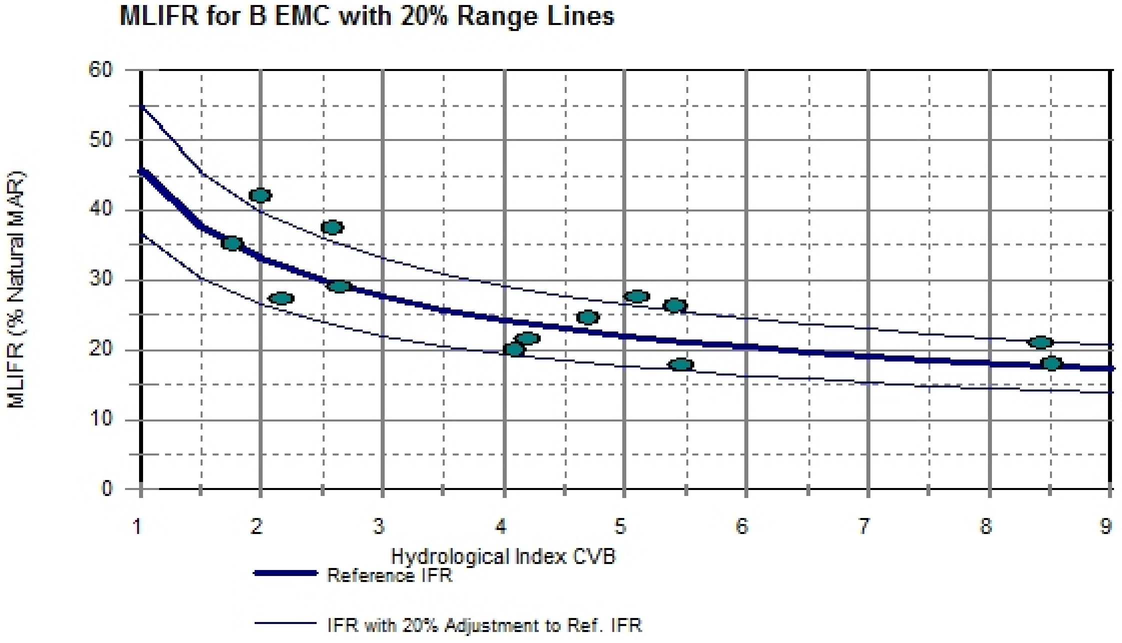


Figure 4.1 Relationship between the annual maintenance low-flow requirement for B-class rivers and their natural hydrology

4.3 Incorporating ecological variation into the IFR DSS estimations

Any effort to incorporate ecological information into a rapid IFR estimation procedure had to be carried out within the constraints imposed by limited data and information. The approach described in this section is largely conceptual and should be seen as a first attempt at identifying relationships between the physical and biological components of rivers and their relative flow requirements.

4.3.1 Identification of ecologically relevant "Modifying Factors"

During past workshops a number of points were raised which suggested possible physical or biological factors and characteristics which may be important determinants of IFRs (such as whether the river is located in a gorge or a floodplain, the type of river bed material, the size of the river and eco-regional differences). The small number of useable IFR workshop results and the "noise" associated with these results however make it impossible to statistically identify firm relationships between past results and any of these characteristics. An additional problem is the fact that no IFR information is available for large parts of the country and especially not for intermittently flowing rivers in the more arid parts. Therefore, even if relationships could be identified between physical or biological characteristics and the flow requirements for regions where IFR data are available, these may not necessarily apply directly to the remaining regions. Finally, many past IFRs were established largely on a site-specific and empirical basis without much consideration being given to the mechanisms which underlie the relationships between flow requirements and habitat or biotic response. **The implication of all this is that as long as data are limited, a conceptual approach will need to be adopted in order to describe the hypothetical relationships between the physical and the biological character of the site and the IFR.**

Specialists experienced in instream flow assessment were consulted in order to make use of expert opinion to identify and discuss relevant generic physical and biological factors ("modifying factors") which were considered to influence IFRs. They were asked to generate hypotheses on how IFRs will be influenced by different categories of the identified modifying factors. The following approach stems from many of these discussions and addresses the need to consider IFRs more mechanistically.

4.3.2 Considerations influencing choice of factors

The following questions were borne in mind when considering possible factors which potentially influence IFRs. In reading through this document the reader is asked to also bear these questions in mind in order to critically assess the choice of modifying factors and classification categories currently included (or excluded) in the ecological component of the desktop estimate.

☐ **Is this factor of relevance to rapid IFR determination?**
When conducting a comprehensive instream flow assessment it is possible to take into account the full complexity associated with each site. For example, the flowering time of individual plant species and the exact emergence period of invertebrates can be taken into consideration and used to motivate for specific flows. This type of detailed assessment is obviously impossible for the purpose of setting a rough estimate of flow requirements as detailed knowledge of the species - specific requirements is not available for most rivers in the country. Therefore, only those factors which are of a more general applicability can be incorporated into a DSS.

☐ **What is the relative importance of this particular factor in terms of influencing IFR determination? Is it negligible or highly deterministic?**
Once the factors have been identified which are most likely to influence IFRs it should be possible to establish a hierarchy of decreasingly important factors. The scoring system which has been developed to incorporate ecological differences into the present DSS is based on the assumption that the relative importance of each factor can be described by a numerical weighting. This is described in greater detail in Section 8.

☐ **What classification categories are of ecological relevance within each factor? Can these be unambiguously defined?**
Each factor can be described by a number of different categories. For example, the possible influence of channel roughness on the IFR is hypothesized to be dependent on whether the channel bed is rough (cobble/boulder) or smooth (sand/gravel) . These categories are considered to be of ecological relevance as they provide different biotopes in which different types of biota can establish. However, it may be possible that further distinction needs to be made within these categories, such as disaggregating "smooth channels" into sand and gravel channels. This is possibly the most difficult obstacle in the path towards incorporating ecological differences into the DSS because, to date, little work has been done to identify or define relevant categories.

☐ **What influence (if any) do the different categories within a factor have on the total IFR? Do they increase or decrease the IFR? Do they influence low-flow requirements, high-flow requirements, or both?**
For example, different categories of valley types(gorge or flood plain) potentially have very little influence on the low-flow requirement. However, significant differences may be found in the high-flow requirements of gorge versus flood- plain systems.

☐ **How does this factor influence seasonal differences in IFRs?**
While different rivers may have similar total IFRs in terms of the annual requirement, significant differences may be found in the seasonal distribution of these flows. Certain ecological factors may

require that a higher proportion of the natural wet or dry season flow is catered for than would be suggested by the regionalised seasonal distribution used in ***RESDSS.*** For example, it might be suggested that a river which has riparian vegetation which requires year-round water to ensure its survival will require a relatively larger proportion of its dry season flow than a river which has riparian vegetation adapted to cope with little or no water in the dry season.

☐ **Is it possible to provide a rough but acceptable quantitative estimate of the influence every factor and category has on the relevant component of the instream flow requirement?**
While "acceptable" remains a highly subjective term it is used here in the context of the relative impact of the individual estimates on each IFR component and the extent to which it modifies the reference hydrological IFR estimate.

☐ **Are data pertaining to the determination of site descriptions of this factor readily available on a regionalised or countrywide basis and at the correct scale? If not, is it possible, and what would be required, to establish such a database?**
This would be a long-term goal. At this stage of the development of the method it should be accepted that if physical and biological data are to be used in the DSS some form of site visit will be required.

4.3.3 Factors influencing the annual maintenance and drought low-flow component

For large-scale Reserve estimation it is practically impossible to take into account species-specific flow requirements when considering possible factors which would influence the annual low-flow requirement. This is largely due to a general lack of information on the specific habitat or water requirements for the wide-range of fauna and flora found in and along South African rivers. Furthermore, setting IFRs based on the requirements of certain species assumes stability in the instream biotic community and, in effect, ignores the natural process of succession. While past IFRs may very well have been set to cater for the flow and water requirements and habitat preferences of certain species, in principle, the setting of low flows using the Building Block Methodology is based on maintaining as much as possible of the natural diversity of habitat. The underlying assumption is that a functional community will be maintained if the following low-flow criteria are met (assuming acceptable water quality is maintained): flows are provided which will cater for the maintenance of natural habitat and habitat heterogeneity; flows are provided which ensure that water remains available to the riparian vegetation at critical periods; and that the natural seasonal distribution is maintained. The variability in low-flow requirements is therefore potentially explained by the variation in physical and biological characteristics of the rivers which influence the ability of a modified flow regime in order to meet these criteria.

A reduction in natural baseflows impacts on the physical habitat template and available resources of the river by changing the natural *temperature regime*, the abundance and proportion of *marginal* and *instream habitat*, the water available to *riparian vegetation*, the *sediment transport capacity* and the *water chemistry*. These can be considered to be the "primary impact variables" affected by baseflow regulation. A change in any of these variables has potential secondary biological impacts due to the associated loss or change in the "natural" conditions required by invertebrates, fish, reptiles and mammals, and the marginal and riparian vegetation. The potential secondary geomorphological consequence of baseflow regulation is a change in the physical channel structure resulting from a reduced ability to maintain suspended sediment mobility. These impacts of low-flow reduction have been summarized in Figure 4.2.

LOW FLOW ------------> PRIMARY IMPACT -----------------------> SECONDARY IMPACT
REDUCTION
> Temperature **> Loss/change in biota**
> Marginal Habitat **> Loss/change in riparian vegetation)**
> Instream Habitat
> Riparian Vegetation **> Change in channel structure**
> Sediment Transport~ **(sedimentation, vegetation**
> Water Chemistry * **encroachment & erosion)**

~ Only considered for maintenance low flows
**** Addressed separately in the setting of the Water Quality Reserve.***

Figure 4.2 Summary of the potential primary and secondary impacts associated with a reduction in baseflows.

The severity or rate of change in any of the secondary impacts is dependent on whether or not a baseflow reduction has a significant impact on the primary impact variable. This, in turn, is influenced by a host of "modifying factors" which either buffer or enhance the impact of the flow reduction on the primary variables. These "modifying factors" may be related to the climate, geology, geomorphology, soils and/or vegetation which are found in the catchment or at the site and, hence, it is expected that the modifying effect will vary both spatially and seasonally.

This is a first attempt to identify the factors which will modify the impact of flow reduction on the primary impact variables. Table 4.1 provides a list of modifying factors influencing each of these primary impact variables, along with the categories within each factor, which are considered to be of ecological relevance. The choice of modifying factors and their associated categories were based largely on the considerations outlined in Section 4.3.2. Explanation of the hypothesized influence of these categories on the IFR will be given in Section 4.4.

The influence of a reduction of flow on the sediment transport capacity is not considered for drought low flows as their sediment transport capacities are assumed to be relatively insignificant under natural conditions. The influence of flow reduction on the water chemistry of the river will not be considered at all as it has been accepted that this issue will be dealt with separately in the setting of the Water Quality Reserve and is beyond the scope of this initial study. However, as information becomes available with respect to which types of systems are more or less susceptible to changes in water chemistry in response to changes in the flow volume, it is expected that it will be possible to incorporate this variable into the Decision Support System as well.

The limited scientific knowledge, which was based on the choice of categories, has led to a very coarse level of classification being adopted at this stage of the project. As understanding increases, the number and definition of categories within each modifying factor can naturally be refined. Furthermore, until clear definitions are provided for the delineation of each of these categories, it will have to be accepted that any description of sites or rivers will remain largely subjective. However, using past IFR results to define a physical reference condition should make it possible to achieve some degree of consistency amongst specialists in their site descriptions.

For a variety of reasons there will be rivers or sites which, despite having similar hydrological and physical characteristics as others, have species or communities which are considered to warrant extra protection (endemics, rare and endangered species) which is considered necessary in order to provide a greater proportion of the natural flow. This difference in instream flow requirements, is essentially based on a value judgement and should therefore be catered for in the choice of ecological management class which automatically provides for greater volumes of flow for the higher management categories. Therefore, the approach adopted in this study ignores differences in individual species requirements and focuses instead on identifying those ecologically relevant physical factors which may generically explain differences in IFRs.

Table 4.1 Potential modifying factors (and their relevant classification categories) influencing the susceptibility of the site to the primary impacts associated with a reduction in maintenance and drought baseflows. (G= Greater, L= Less)

Primary Impact	**Modifying Factor**	**Classification Categories**		**Susceptibility**
Temperature Increase	Rainfall Region	Winter		G
		Summer/Aseasonal		L
	Depth	Significantly shallow		G
		Deep		L
	Velocity	Significantly slow-flowing		G
		Fast-flowing		L
	Channel Shading	Not shaded in summer		G
		Shaded in summer		L
Reduction in Marginal Habitat	Channel X-Sectional Shape	Parabolic		G
		Rectangular		L
	Channel Pattern	Multi-thread		G
		Single thread		L
Reduction in Instream Habitat	Channel X-Sectional Shape	Rectangular		G
		Parabolic		L
	Channel Pattern	**Maintenance**	**Drought**	
		Single thread	Multi-thread	G
		Multi-thread	Single thread	L
	Channel Roughness	**Maintenance**	**Drought**	
		Smooth (sand/gravel)	Rough (boulder/cobble)	G
		Rough (boulder/cobble)	Smooth (sand/gravel)	L
	Gradient	Steep		G

		Flat	L
Riparian Vegetation Stress	Channel Type	Bedrock	G
		Alluvial	L
	Channel Pattern	Multi-thread	G
		Single Thread	L
Decreased Sediment Transport Capacity **(Maintenance low flows only)**	Catchment Sediment Yield	High	G
		Low	L
	Grain Size	Coarse	G
		Fine	L
	Gradient	Flat	G
		Steep	L
	Channel Geometry	Low width:depth ratio (narrow-deep)	G
		High width:depth ratio (wide-shallow)	L
	Substrate Type	Boulder/cobble	G
		Sand/gravel	L

Note: In this table the last column refers to the relative susceptibility of the classification categories to the primary impact associated with a low flow reduction. For example, winter rainfall region rivers are considered more susceptible to an increase in temperature in response to a low flow reduction than summer rainfall region rivers.

4.3.4 Factors influencing the maintenance low-flow seasonal distribution

The current DSS distributes annual low-flow volumes on the principle of maintaining the seasonal pattern of the natural baseflow regime accepting, however, that a higher proportion of the natural monthly flow is required during the dry months than during the wet months. Currently this seasonal distribution is based on a regionalised set of parameters which have been determined from a countrywide analysis of the seasonal baseflow characteristics of South African rivers (Cobbing, 1998; Hughes & Münster, 1999). It has been possible to identify 20 regions by their characteristic baseflow distributions.

Within any one region it is expected that the low-flow seasonal distribution will, however, be influenced not only by the hydrology but also by the physical and biological characteristics defining different sites or rivers within that region. Setting a modified flow regime which doesn't take into account these physical and biological characteristics will potentially impact on the biota and the channel structure. These potential primary impacts are: stress to the *riparian vegetation*; reduction in dry season *instream habitat*; reduced *sediment transport*; reduced *migration*; and loss of flow in *secondary channels or distributaries*. Therefore, the shape of the modified flow regime (determined by the relative proportion of the natural flow required in the wet or the dry season) is expected to be influenced by a host of modifying factors which all, in some respect, have a seasonal component. Table 4.2 summarizes the modifying factors and their associated classification categories for each of the primary impacts. The hypothesized reason and influence of these modifying factors is outlined in Section 4.5.

Although it is expected that the location of rivers in different rainfall regions influences the seasonal distribution, these influences should be reflected in the different regional monthly distributions. This factor is therefore not considered further at this stage. At this point no attempt has been made to identify factors which potentially modify the seasonal distribution of drought low flows.

Table 4.2 Potential modifying factors (and their relevant classification categories) influencing the shape of the low-flow seasonal distribution. (F= Flatter distribution; S= Steeper distribution)

Primary Impact	**Modifying Factor**	**Classification Categories**	**Influence**
Riparian Vegetation Stress	Riparian Water Requirement	Year-round water requirement	F
		Seasonal water requirement	S
Reduced Instream Habitat	Large Mammals/Reptiles	Present	F
		Absent	S
Reduced Sediment Transport	Wet Season Sediment Input	Insignificant	F
		Significant	S
Reduced Migration	Migratory Species	Absent	F
		Present	S
Loss of flow in Secondary Channels/Distributaries	Type of Flow	Perennial	F
		Seasonal	S

Note: The last column describes the relative influence each classification categories is expected to have on the maintenance low-flow seasonal distribution. For example, to reduce potential riparian vegetation stress rivers which have riparian vegetation requiring water year-round for survival should have flows distributed more evenly throughout the year (*i.e.* have a flatter distribution).

4.3.5 Factors influencing the annual maintenance high-flow component

Unlike low flows which are required predominantly for the maintenance of habitat, high flow events are required to fulfill a range of different functions which include maintenance of channel geomorphology; mobilization of sediment; inundation of flood plains and recharge of isolated pools and aquifers; activation of seasonal side channels; provision of suitable habitat for riparian vegetation; and provision of cues for spawning and migration. This makes the setting of high flow requirements inherently more complex than low flow requirements as consideration needs to be given not only to the magnitude of required flows but also to the frequency, timing and duration of events. However, in the desktop estimate these issues are simplified somewhat because results are required only as a time series of monthly volume requirements. This suppresses the need to provide details of peaks and durations of events and the need to specify how many events are required within a single month.

Despite the constraints imposed by an inadequate understanding of high flow events certain general physical and biological factors can be identified which logically would result in differences in the annual high-flow requirement. As with annual low flows rivers are considered in terms of physical and biological modifying factors which influence the relative susceptibility of a site or a river to the primary impacts associated with a reduction in high flows. These primary impacts are: reduced *floodplain inundation*; reduced *sediment mobilization*; reduced *activation of seasonal channels and pools*; and stress to the *riparian vegetation*. Table 4.3 summarizes the modifying factors and the classification categories which influence the magnitude of annual high flow events.

Table 4.3 Potential modifying factors (and their relevant classification categories) influencing the susceptibility of the site to the primary impacts associated with a reduction in maintenance high flows. (G= Greater; L= Lesser)

Primary Impact	Modifying Factors	Classification Categories	Susceptibility
Reduced Flood Plain Inundation	Valley Type	Flood plain present	G
		Flood plain absent	L
Reduced Sediment Mobilization	Catchment Sediment Yield	High	G
		Low	L
Reduced Activation of Seasonal Channels and Pools	Channel Pattern	Presence of temporary pools and side channels	G
		Absence of temporary pool and side channels	L
Riparian Vegetation Stress	Habitat Requirements	Presence of bedrock dependent species	G
		Absence of bedrock dependent species	L
	Connectivity of Active Channel and Subsurface Water	Poor	G
		Good	L

Note: In this table the last column refers to the relative susceptibility of the classification categories to the primary impact associated with a high-flow reduction. For example, rivers which have a flood plain are obviously more susceptible to the loss of flood plain inundation resulting from a high-flow reduction than rivers which are not located within a flood plain.

It needs to be stressed that at this point categories associated with the modifying factors remain very broad given the lack of knowledge surrounding high flows. For example, the size of a flood plain will obviously influence the magnitude of the high flow needed to meet inundation requirements, however, at this stage it is only feasible to differentiate between whether a flood plain is present or absent. Consideration is not given to the high flows required for the purposes of migration. It is assumed that the higher magnitudes required will already have been catered for in the setting of the Ecological Management Class which takes into account presence or absence of migratory species.

As drought high-flow requirements are considered insignificant for planning purposes they are not estimated by the DSS and will therefore not be considered further at this stage. Modifying factors are therefore specific to maintenance high flows.

4.3.6 Hypothesized Influence of "Modifying Factors" on the IFR

With respect to the influence of physical and biological factors on the annual or seasonal low- and high-flow requirements it is necessary to consider each modifying factor in isolation. The question asked was: "All other factors being equal at two sites or rivers, what influence would a difference in a single modifying factor have on the annual low-flow/high-flow requirement or seasonal distribution?"

Obviously the final IFR will reflect the integrated effects of a complex set of site-specific, interrelated variables, and therefore it may be argued that considering the effect of individual factors in isolation is far too simplistic. However it is hoped that disassembling these various components, and formulating hypotheses on their individual effects, may prove to be a useful step on the road toward a fuller understanding of IFRs in general, and toward a more mechanistic approach to instream flow assessment. **It is expected that initially these hypotheses may largely be a reflection of the "gut-feel" of the river scientists, and be based on what seems logical, however it is hoped that future studies, both locally and internationally, will provide a more scientific basis for substantiating or refuting these initial hypotheses. This "first attempt" may prove useful as a framework and provide direction for future research efforts.**

Specialists need to consider at which spatial scale these modifying factors should be assessed. In other words, should definition of a river's physical characteristics be based on the characteristics describing the most sensitive site (the chosen IFR site), or rather on the general characteristic which could be used to describe the entire section of the river affected by the flow reduction? For the sake of simplicity the hypotheses will refer to different susceptibilities between "sites" until clarity is obtained as to which factors need to be assessed at the site scale, and those which need to be assessed at the section scale.

4.4 Influence of modifying factors on the annual maintenance and drought low-flow requirement

In order to maintain a healthy and functioning community, resembling the natural or historic community as far as possible, estimations of the maintenance and drought low flow IFR for different sites needs to take into account the differential impact of flow reduction on the river's primary variables. It is proposed that sites which, due to their physical and biological characteristics, are more susceptible to a change in their primary variables will be more at risk of suffering the negative secondary impacts of a flow reduction than sites which are considered to be less susceptible to these changes (refer to Table 4.1, Section 4.3.3). It is therefore hypothesized that sites which are relatively more susceptible to a change in their primary impact variables would require a relatively greater proportion of their natural baseflows than less susceptible sites in order to be buffered against the impacts of baseflow reduction.

The following sections describe the hypothesized influence of the modifying factors on both the maintenance and drought annual low-flow requirement.

4.4.1 Factors Influencing the Susceptibility to an Increase in Temperature

Flow reduction is generally considered to result in an increase in temperature. It is hypothesized that the same percentage reduction in flow will have different effects on the degree to which temperatures change depending on the specific characteristics of the site. The following characteristics defining the river type are considered to be modifying factors: *rainfall region, depth, velocity* and *channel shading*. When deciding what category of depth, velocity or channel shading best describes the site, it is proposed that this description be based on the general character of the entire section which is affected by a reduction of baseflows. It should be noted at this point that some specialists do not perceive temperature to be an important determinant of IFRs as biota are tolerant within a fairly wide range of temperatures. However, as one of the frequently quoted impacts of large dams is an increase in downstream temperature, this physical variable is included at this stage. It should also be noted that the mechanism of release of water from dams (from the top or bottom strata of the stored water) can have a substantial impact on downstream temperatures.

Rainfall regions (winter/summer/aseasonal)

It is hypothesized that winter rainfall region rivers are more susceptible to a biologically significant change in temperature, in response to the same percentage reduction in flow, than summer rainfall region rivers. This suggests relatively greater annual maintenance and drought low-flow requirements for winter rainfall region rivers.

Summer is the season considered to be of greatest biological importance to biota as this is the time at which they are actively involved in feeding, breeding and moving around. Hence, the fauna is considered to be most exposed and susceptible to thermal factors in the summer months (Stuckenberg, 1969) and, therefore, it is important to consider the effect of a flow reduction on water temperatures during this time. This critical period coincides with the dry season (period of lowest flows) in the winter rainfall region. The increased insolation, coupled with the absence of high-flow events to maintain acceptable temperatures, means that there is a relatively higher risk of a flow reduction resulting in a critical increase in the summer water temperatures in a winter rainfall river than in a summer rainfall river. For this reason, it is considered a necessary precaution to maintain a higher proportion of the natural baseflow in winter rainfall than in summer rainfall region rivers.

It is speculated that aseasonal rivers will have flow requirements which are closer to those of winter than summer rainfall region rivers as many of these rivers can experience extended low-flow periods in summer. However, assessing the potential susceptibility of aseasonal rivers to a biologically significant increase in temperature may require site-specific assessment of the hydrology to determine typical length and timing of low-flow periods.

Depth (significantly shallow/insignificant)

It is hypothesized that the susceptibility of a site to an increase in temperature, resulting from a reduction in flow, is influenced by the mean depth of the section affected by flow reduction. This suggests relatively greater annual maintenance and drought low-flow requirements for sites whose associated sections are shallow enough for a flow reduction to have a biologically significant impact on the natural water temperature.

The variability in river depth at any one site, and within the section impacted by flow reduction, makes this modifying factor incredibly difficult to define rivers. Any regionalisation which attempts to establish a relative measure for depth will need to take into account this temporal and spatial variability. Another major obstacle to incorporating depth into the DSS is obviously the lack of clarity in defining "significantly shallow." It is probable that there will not be one single depth which can be defined as the depth below which flow reduction has a critical effect on temperature as this depth may vary for different rivers. For example, a shallow river which has a darker substrate (therefore lower albedo) may be relatively more susceptible to a flow-reduction-induced temperature increase than a river of the same shallowness, but which has a lighter coloured substrate. Additionally, the amount of total suspended solids in the water may have a significant influence on the albedo of the water column and may therefore also explain differences in the depth at which flow reduction results in a biologically significant temperature increase.

Velocity (significantly slow-flowing/insignificant)

It is hypothesized that slow-flowing sections are more susceptible to a biologically significant change in temperature, in response to the same percentage reduction in flow, than fast-flowing sections. This suggests relatively greater annual maintenance and drought low- flow requirements for sites whose associated sections are considered to have a flow rate which is slow enough for temperature to be significantly influenced by a flow reduction.

It should be possible to develop a method for describing sections on the basis of their mean velocities. For this purpose, river slope (measured at an appropriate scale) may serve as a useful and readily- accessible surrogate measure of velocity as steeper gradients are generally associated with more rapid flow. At this stage, however, no categories of velocity have been defined and, therefore, classification of "significantly slow-flowing" remains largely subjective.

Channel shading (summer shading/no summer shading)

It is hypothesized that a section whose channel is shaded during the summer will be less susceptible to a biologically-significant increase in temperature, resulting from a flow reduction, than a section which is not shaded. This suggests that shaded channels should, therefore, have lower annual maintenance and drought low-flow requirements than non-shaded channels.

Identification of rivers as being either shaded or non-shaded will largely depend on site visits as it is unlikely that a general regionalisation will be able to be developed for this factor or a surrogate measure for shading is found.

4.4.2 Factors Influencing the Susceptibility to a Reduction in Marginal Habitat

Marginal habitats, found along the periphery of the main thalweg channel, are often important biotopes as they serve as habitat and refuge areas for invertebrates and juvenile fish. A reduction in the abundance or availability of this habitat type thus has potentially serious biological consequences. Therefore, flow requirements should take into account the need to maintain marginal habitat at sites where this is an important biotope. However, certain physical characteristics influence how susceptible a site is to a loss of marginal habitat when normal and drought baseflows are reduced. These modifying factors are: *cross-sectional channel shape* and *channel pattern*. Additionally, rivers which do not have any possible sites or tributaries which will serve as refuge areas for marginal habitat-dependent biota during drought periods, should have a higher drought low-flow requirement than rivers in which refuge areas are present naturally.

Cross-sectional channel shape (parabolic/rectangular)

It is hypothesized that, for the same percentage reduction in flow, channels which have a roughly parabolic channel cross-sectional shape will be more susceptible to a loss of marginal habitat than channels which are of a rectangular shape. This suggests that if marginal habitat is an important biotope at a particular site then sites at which channel cross-sectional shape is parabolic will have relatively greater maintenance and drought low-flow requirements than those at which cross-sectional shape is rectangular.

This hypothesis is based on the idea that channel cross-sectional shape influences whether a flow reduction will result in a relatively greater loss of wetted perimeter (and hence, marginal habitat) than in the case of depth and velocity (instream habitat). It seems logical to suggest that in more parabolic-shaped channels (those rivers where sediment deposition has resulted in the creation of lateral bars or which have a deeper thalweg within a relatively shallow channel) a reduction in baseflow will result in a relatively large change in wetted perimeter for a small corresponding loss of depth and velocity. On the other hand, the impact of a flow reduction on the hydraulic geometry in rectangular channels will be a relatively rapid loss of depth and velocity with very little change in wetted perimeter. Therefore, it is suggested that parabolic channels are more susceptible to a loss of marginal habitat, whereas rectangular channels are more susceptible to a loss of depth and velocity.

In practice, a problem arises due to the difficulty of identifying and defining the channel cross-sectional shape for a site. If this factor is to be of any practical value, consensus needs to be reached in terms of what discharge level(s) should be used to define cross-sectional channel shape. In reality, channel shape may change in response to fluctuations in discharge. For example, during the wet season the mean flow may result in a roughly rectangular channel shape. Any reduction in wet season low flows will then have a greater impact on depth and velocity than wetted perimeter. However, the channel which contains the dry season low flows may be more parabolic and, hence, a reduction in dry season flows will result in a more rapid loss of marginal habitat.

Recognising that the definition is largely dependent on the water level, and that the instream flow requirement is influenced by definition of channel shape, it may be useful, for site-specific analysis, to define the channel forms related to the natural or historical mean wet and dry season water level for both normal and drought conditions. This will allow flow requirements to be set for the different IFR seasonal components (maintenance wet and dry season, and drought wet and dry season) based on intra-site differences in cross-sectional channel shape. This would require mapping the channel cross-sectional profile and hydraulic analysis.

For countrywide instream flow estimation, and in cases where no ground work is conducted, such detailed assessment to define channel shape is impossible. If this ecological component of the DSS is to be used for these purposes, rather than just for site-specific estimation, it is necessary to develop a rapid method for determining roughly the channel cross-sectional shape. It may, for example, be possible to identify a coarse relationship between channel shape and location of the site in the longitudinal profile. In this case, reach gradient may then be found to be a suitable surrogate variable for channel shape and one which is easily obtained from a 1:50 000 map. This, however, needs to be tested.

Channel pattern (multi-thread/single thread)

It is hypothesized that, due to the greater proportion of marginal habitat associated with multi-thread than with single-thread rivers, multi-thread channels will have relatively greater maintenance and drought low-flow requirements.

This hypothesis is based on the assumption that the greater wetted perimeter of multi-thread channels will result in a greater amount of marginal habitat being available. Additionally, the presence of various side channels provides a high diversity of marginal habitats and allows the establishment of a highly diverse community of species. It is assumed that the biological impact associated with a loss of marginal habitat, in terms of loss of diversity, is thus potentially greater in multi-thread channels than in single- thread channels.

Side channels in multi-thread systems may be perennially or seasonally flowing. In terms of annual low-flow requirements, it seems logical to set higher requirements for the perennial system than for the seasonal system.

4.4.3 Factors Influencing the Susceptibility to a Reduction in Instream Habitat

A reduction in flow will result in a decrease in depth and velocity in the active channel. These are the important parameters defining the instream habitat and a change in either depth or velocity can be expected to have biological consequences at sites where instream habitat may be an especially important or relatively more important biotope (for example, gravel and cobble bed sites). Characteristics influencing the susceptibility of sites to a loss of instream habitat with a reduction in flow are: *cross-sectional channel shape, channel pattern, channel gradient* and *channel roughness*. Additionally, rivers which do not have any possible sites or tributaries which will serve as refuge areas for instream habitat- dependent biota during drought periods, should have a higher drought low-flow requirement than rivers in which refuge areas are naturally present.

Cross-sectional channel shape (parabolic/rectangular)

It is hypothesized that, for the same percentage reduction in flow, channels which have a roughly rectangular channel cross-sectional shape will be more susceptible to a loss of instream habitat than channels which are of a parabolic shape. This suggests that if instream habitat is an important biotope at a particular site then channels which are of a rectangular cross-sectional shape will have relatively greater maintenance and drought low-flow requirements than parabolic- shaped channels.

Refer to Section 4.4.2 ("Cross-sectional channel shape") for explanation and discussion of this factor.

Channel pattern (single thread/multi-thread)

It is hypothesized that, for the same percentage reduction in flow <u>under normal climatic conditions</u>, single thread rivers are more susceptible to a loss of instream habitat than multi-thread channels. This suggests that if instream habitat is an important biotope at a particular site, then single-thread channels will have greater maintenance low-flow requirements than multi-thread channels.

Conversely however, it is hypothesized that <u>under drought conditions</u>, and for the same percentage reduction in flow, multi-thread channels will be more susceptible to a loss of instream habitat as side channels are at risk of drying out completely. This suggests that multi-thread channels will have relatively greater drought low-flow requirements than single thread channels.

The relatively higher maintenance low-flow requirement for single-thread rivers under normal conditions is based on the assumption that the impact of the flow reduction in a multi-thread channel is spread across a number of side channels and that the overall change in depth and velocity in the main channel of a multi-thread system is less than in a single-channel system of similar dimensions.

On the other hand, the relatively greater requirement for multi-thread channels under drought conditions reflects the thinking that the impact of a flow reduction on the integrity of the site as a whole may be far greater in a multi-thread channel system, due to the greater risk of a complete loss of flow (or a loss of critical depth) in some, or all, of the side channels during drought conditions. These side channels are considered to be important as their different flow hydraulics support the establishment of a very different composition of species than those found in the main channel. The impact, in terms of loss of species diversity will, therefore, potentially be far greater (for a similar percentage reduction in flow) in a multi-thread system than in a single-channel system.

It is expected that the relative maintenance and drought low-flow requirements for multi-thread vs single-thread channels will be controversial. So far there has been no clear agreement between specialists as to whether or not multi-thread channels have different flow requirements than single-thread channels. These hypotheses will, therefore, in all likelihood need refinement once greater clarity and agreement is reached on this issue. However, it is hoped that, considering their relative requirements in terms of their relative susceptibility to loss of marginal and instream habitat, a starting point for further discussion and work will be established.

Channel roughness (smooth/rough)

It is hypothesized that, for the same percentage reduction in flow under normal climatic conditions, sites which have a smooth channel bed (sand/gravel) are more susceptible to a loss of instream habitat than sites which have a rough bed (cobble/boulder). This suggests that if instream habitat is an important biotope at a particular site then "smooth" channels will have relatively greater maintenance low-flow requirements than "rough" channels.

Conversely however, it is hypothesized that under drought conditions, and for the same percentage reduction in flow, "rough" channels will be more susceptible to a loss of instream habitat as they are at a greater risk of losing abundance of habitat. This suggests that if instream habitat is an important biotope, then "rough" channels will have relatively greater drought low-flow requirements than "smooth" channels.

There is a great deal of uncertainty surrounding these two hypotheses. However, they are based on the assumption that under normal climatic conditions the negative effects of a loss of depth and velocity in rough channels is somewhat reduced or balanced by the potential increase in habitat heterogeneity which facilitates the establishment of a more diverse community. For example, whereas initially only deep and intermediate depth habitats were found in rough channels, a reduction in depth has the potential to create shallow habitat, while still maintaining areas of sufficient depth to provide "deep habitats". On the other hand, a reduction in flow is expected to have no effect on habitat diversity in smooth channels.

The reversal of the hypotheses under drought conditions is explained by the assumption that the low levels of flow will result in a complete loss of flow in the areas which under maintenance conditions provided shallow habitat. It is expected that the impact on the abundance of remaining useable habitat will be greater in a rough channel than in a smooth channel owing to the rough substrate having the effect of minimizing the wetted channel area.

Gradient (steep/flat)

It is hypothesized that, for the same percentage reduction in flow, sites which have a relatively steeper gradient will be more susceptible to a loss of instream habitat than rivers which have a flatter gradient. This suggests that if instream habitat is an important biotope at a particular site, then sites which have a steep gradient will have relatively greater maintenance and drought low-flow requirements than low-gradient sites.

This hypothesis is based on the assumption that a greater amount of water is required in order to meet the depth requirement at those sites which have a steep gradient. A practical consideration is deciding what the appropriate scale is for the measurement of slope. For example, should sites be described in terms of the gradient of the reach (bedrock-fall, cascade, pool-riffle etc.) or in terms of the geomorphological zone in which it is located (mountain stream, foothill, lowland sand bed etc.). Furthermore, a means of differentiating between "steep" and "flat" gradients needs to be developed so as to reduce the subjectivity involved in describing a reach/zone as "steep" or "flat".

4.4.4 Factors Influencing the Susceptibility to Riparian Vegetation "Stress"

A reduction in flow will reduce the amount of water which is available to riparian vegetation. For these purposes, riparian vegetation is defined as that vegetation which is dependent, either directly or indirectly, on the river to ensure that its water demands are met. Water may be available directly from the active channel, or indirectly from subsurface water which is maintained and recharged by flow in the channel. Clearly this factor is only relevant at sites where riparian vegetation has a significant water requirement. Factors influencing the relative flow requirement are the *type of channel* and the *channel pattern.*

Channel type (bedrock/alluvial)

It is hypothesized that, for the same percentage reduction in flow, bedrock sites are more susceptible to a reduction in the availability of water to the riparian vegetation than alluvial sites. This suggests that if riparian vegetation has significant water requirements, then sites which have bedrock channels will have relatively greater maintenance and drought low-flow requirements than alluvial channels.

In bedrock sections there is a relatively greater risk that a reduction in flow will result in a loss of connectivity between the riparian vegetation and its water source.

Channel pattern (multi-thread/single thread)

It is hypothesized that if riparian vegetation has significant water requirements then multi-thread channels will have relatively greater maintenance and drought low flow requirements than single thread channels.

While this factor does not actually relate to the different susceptibilities of sites to the impacts of flow reduction, it has been included as a modifying factor as it is considered to be a significant determinant of differences in instream flow requirements. It is proposed that as multi-thread channels have a greater amount of wetted perimeter than single channels, this will allow the establishment of a greater amount of riparian vegetation. This will naturally result in a greater overall riparian water demand and, therefore, a greater amount of flow will be required in multi-thread channels to meet this higher demand.

4.4.5 Factors Influencing the Susceptibility to a Reduction of Sediment Transport Capacity

The transport of suspended sediments is a function of both the flow velocity (and hence, the gradient of the river), the channel geometry and the grain size. A flow reduction is expected to reduce the ability of the river to maintain the mobility of suspended sediments. In rivers where baseflow plays a significant role in maintaining sediment mobility, a reduction in these flows potentially results in an increased rate of sedimentation. The resultant loss of unsilted cobble and gravel reaches impacts on instream biota as these substrates provide important habitats for juvenile fish and invertebrates. Additionally, an increase in sediment deposition can lead to channel bar development which, in turn, facilitates vegetation encroachment into the river channel. The susceptibility of sites to the negative impacts associated with a change in the sediment transport regime is expected to be influenced by the following modifying factors: *catchment sediment yield, input sediment grain size, gradient, channel geometry* and *substrate type.*

The impact of flow reduction will not be considered for drought conditions as it is presumed that even under natural conditions drought flows are relatively insignificant in terms of their sediment transport capacities.

Catchment sediment yield (high/low)

It is hypothesized that, for the same percentage reduction in flow, rivers located in catchments which have a high suspended sediment yield will be more susceptible to a reduction in sediment transport capacity than rivers located in low sediment-yielding catchments. This suggests that, if low flows are considered to be significant in terms of their role in sediment transport, sites located in catchments, which have a high sediment yield, will have relatively greater maintenance low- flow requirements than sites located in catchments which have a low or insignificant sediment yield.

This concept is similar to that of the assimilative capacity of rivers. It is assumed that for a given flow, rivers can maintain a certain amount of sediment mobility. As flows decrease, the amount of sediment which can be transported becomes less and, therefore, any additional sediment will be deposited. Rivers with high sediment loads will, therefore, be at a greater risk of their transport capacity being exceeded when baseflows are reduced than rivers which have smaller sediment loads. Thus, to reduce the risk of sedimentation a greater proportion of the natural flow is required by rivers located in catchments which have a high sediment yield.

The lack of definition of “high” and “low” in terms of sediment yield currently makes an assessment of this characteristic very subjective. On an international scale, most of South Africa’s catchments have high sediment yields due to a combination of highly erodable soils, poor vegetation cover and poor land use practices. However, it may be possible to distinguish catchments or regions within the country which have relatively low sediment yields. Rooseboom’s map of sediment yield’s in South African catchments may prove to be a useful starting point for this type of categorisation (Rooseboom et al., 1992). A standard definition of “high” and “low” is required so that it can be applied at a national scale.

Grain size (coarse/fine)

It is hypothesized that, for the same percentage reduction in flow, rivers located in catchments which yield relatively coarse sediments will be more susceptible to a reduction in sediment transport capacity than rivers located in catchments which yield relatively fine sediments. This suggests that, if low flows are considered to be significant in terms of their role in sediment transport, rivers which transport relatively coarse sediment will have greater maintenance low-flow requirements than rivers which transport relatively fine sediment.

Grain size is considered to influence the low-flow requirement as a relatively greater velocity is needed to maintain coarse sediments in suspension than is needed for fine sediments. At this stage, however, the lack of a clear definition of “coarse” and “fine” grain size, which is relevant to differentiating between sediment transport capacities, makes description of this factor subjective.

Gradient (flat/steep)

It is hypothesized that, for the same percentage reduction in flow, sites located in flat reaches/zones will be more susceptible to a reduction in sediment transport capacity than sites located in steep reaches/zones. This suggests that, if low flows are considered to be significant in terms of their role in sediment transport, sites located in reaches/zones which are relatively flat will have relatively greater maintenance low-flow requirements than sites located in steep reaches/zones.

This is based on the assumption that in flat reaches a relatively greater volume of water is required to produce the velocity required to maintain sediments in suspension.

A practical consideration is what the appropriate scale is for measurement of slope. For example, should sites be described in terms of the gradient of the reach (bedrock-fall, cascade, pool-riffle etc.) or in terms of the geomorphological zone in which it is located (mountain stream, foothill, lowland sand bed etc.). Furthermore, a means of differentiating between "steep" and "flat" gradients needs to be developed so as to reduce the subjectivity involved in describing a reach/zone as "steep" or "flat".

Channel geometry (narrow-deep/wide-shallow)

It is hypothesized that, for the same percentage reduction in flow, sites which have a low channel width:depth ratio (narrow and deep channels) will be more susceptible to a reduction in sediment transport capacity than sites which have a high channel width:depth ratio (wide-shallow channels). This suggests that, if low flows are considered to be significant in terms of their role in sediment transport, narrow and deep channels will have relatively greater maintenance low-flow requirements than sites which have a wide and shallow channel.

Channels which are relatively wide and shallow have a better sediment transport capacity. It is expected that their ability to maintain sediments in suspension will be greater than rivers which have narrow and deep channels. While these classification categories currently remain subjective the width:depth ratio provides the potential to define these categories quantitatively.

Substrate type (boulder-cobble/sand-gravel)

It is hypothesized that, for the same percentage reduction in flow, sites which have a boulder/cobble substrate will be more susceptible to a reduction in sediment transport capacity than sites which have a sand or gravel substrate. This suggests that, if low flows are considered to be significant in terms of their role in sediment transport, boulder or cobble sites will have relatively greater maintenance low-flow requirements than sand/gravel sites.

The existence of slack water areas in association with boulder or cobble substrates results in a relatively greater rate of sediment deposition (due to the decreased velocities in these slack water areas) than in sand or gravel bed reaches. This deposition is exacerbated by a flow reduction and, therefore, relatively higher flows are required at these sites in order to minimize excessive sedimentation.

Furthermore, it may be relatively more "biologically" important to maintain sediments which are mobile in boulder or cobble bed reaches than in sand bed reaches as sediment deposition in the former will result in the potential loss of important invertebrate and juvenile fish habitat. This would justify the provision of relatively higher low flows for boulder or cobble bed rivers.

4.5 Influence of modifying factors on the maintenance low-flow seasonal distribution

Plotting a seasonal distribution of monthly IFR values produces a curve which roughly mimics the shape of the natural baseflow regime. However, it is suggested that a number of ecological factors influence the wet and dry season flow requirements and, potentially, result in a "flattening" or "steepening" of the distribution. For example, if a factor requires that a greater proportion of the annual total is allocated to the dry season months than initially estimated by the regionalised distribution, this will result in a flattening of the curve (dry season proportion increases while wet season proportion decreases in order to maintain the same annual total). This is illustrated in Figure 4.3. Details of how this modification to the seasonal distribution is achieved is explained in the main report.

The following modifying factors are considered to influence the seasonal distribution of the annual maintenance low-flow requirement: *the riparian vegetation water requirement; the presence or absence of* *large mammals or reptiles; the wet season sediment input; the presence or absence of migratory species; seasonality/perenniality of side channel flow; and the sediment transport requirement.* These factors will only influence the seasonal distribution if they are considered to have a significant influence on the annual low-flow requirement as well.

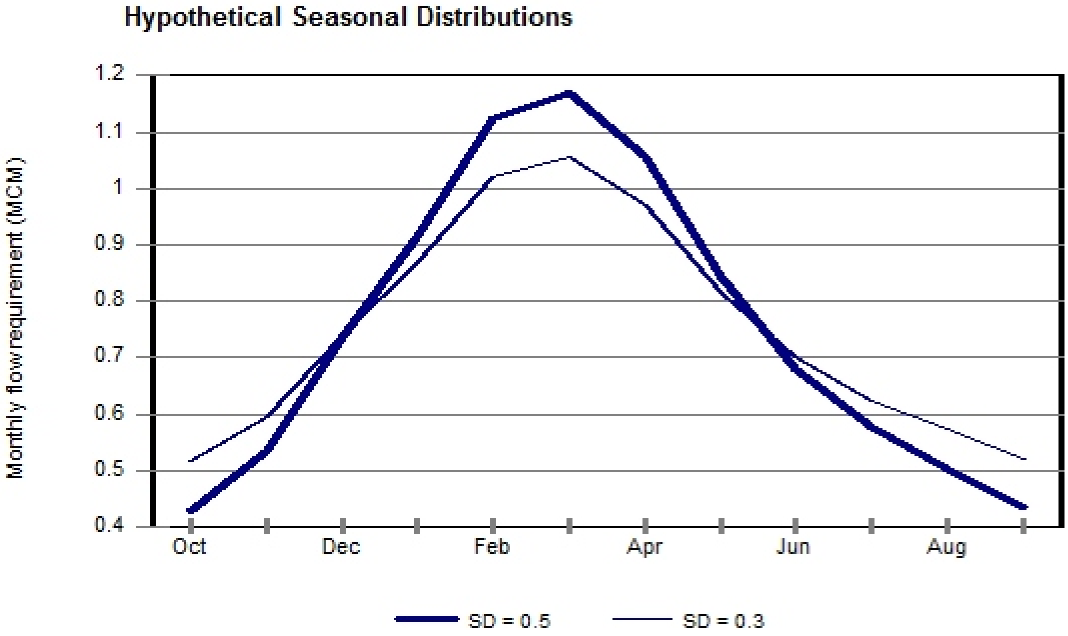


Figure 4.3 Example of a 40% change in the SD parameter value for a particular seasonal low-flow distribution which corresponds with a 28.4% reduction in the range of wet and dry season flows (flattening of the seasonal distribution).

4.5.1 Factors influencing the susceptibility to riparian vegetation "stress"

Setting a seasonal distribution which doesn't take into account the type of riparian vegetation found along a river risks setting flows which do not adequately meet the *requirements of the riparian vegetation.* Whether or not the riparian vegetation requires water throughout the year for its survival is, therefore, an important factor which influences the seasonal distribution.

Riparian water requirement (year-round/seasonal)

It is hypothesized that sites at which riparian vegetation requires water throughout the year for survival will have a "flatter" seasonal distribution than sites at which riparian water demands are only seasonally significant. In other words, a relatively greater proportion of the natural dry season flow needs to be provided at sites which have a significant riparian water requirement throughout the year.

Using evergreen and deciduous species as determinants of whether water requirements are seasonal or continuous is not considered to be accurate. Furthermore, it is unlikely that information on the seasonality or continuity of riparian water use can be regionalised or generalised from existing information. Therefore, assessment of this factor will depend on ground-based investigation of the type of species found at a particular site

4.5.2 Factors influencing the susceptibility to a reduction in instream habitat

During the dry season it is natural for the abundance of instream habitat to decrease. However, a modified flow regime needs to take into account whether or not *large mammals and reptiles* are present to avoid reducing instream habitat to below critical limits in the dry season.

Large mammals and reptiles (present/absent)

It is hypothesized that sites at which large mammals and reptiles are present will require the maintenance of sufficiently deep pools throughout the year. In other words, a relatively greater proportion of the natural dry season flows needs to be provided at sites where large mammals and reptiles are present in order to ensure that sufficient habitat is maintained for them throughout the dry season. The result will be a "flatter" seasonal distribution than that set for sites where this large fauna is absent.

It is uncertain at this stage whether this factor has a significant influence on the seasonal distribution. It has been included at this stage to promote further discussion.

4.5.3 Factors influencing the susceptibility to a reduction in sediment transport

By taking into account whether or not *wet season sediment input* is significant or not, the seasonal distribution can be modified in order to mimimize the risk of excessive sediment deposition.

Wet season sediment input (significant/insignificant)

It is hypothesized that sites which experience high levels of sediment input during the wet season will have a steeper seasonal distribution than sites where sediment input is insignificant. In other words, a relatively greater proportion of the natural wet season flows needs to be provided at sites which have significant wet season turbidity levels in order to ensure that flows are of sufficient magnitude to maintain the input sediments in suspension and to prevent excessive deposition.

Sediment transportation is considered to have a seasonal component due to the fact that sediments predominantly enter the river during the wet season when they are eroded from the catchment by precipitation events. The definition of sediment input as either "significant" or "insignificant", however, remains subjective.

4.5.4 Factors influencing the susceptibility to a reduction in migration

It is expected that the seasonal distribution is modified by whether or not the river or site is inhabited by *migratory species* which rely on wet season flows to facilitate their migration. Taking this factor into account will reduce the risk of losing species which rely on migration to complete one of their life stages.

Migratory species (present/absent)

It is hypothesized that rivers, which are inhabited by migratory fish or eels which depend on a relatively high proportion of the natural baseflow being maintained in the wet season to facilitate migration, will have a steeper seasonal distribution. In other words, a relatively greater proportion of the natural wet season flow should be provided in those rivers that have migratory species which depend on sufficient low flows in order to facilitate migratory passage.

It is uncertain at this stage whether this factor has a significant influence on the seasonal distribution. It has been included at this stage to promote further discussion.

4.5.5 Factors influencing the susceptibility to a loss of secondary channels and distributaries

In order to minimize the risk of losing secondary channels and distributaries in response to a reduction in baseflows, it is necessary to take into account the *type of flow* which is found in these channels.

Type of flow (seasonal/perennial)

It is hypothesized that if secondary channels or distributaries are present and flow naturally during the wet season, only then will the seasonal distribution be steeper than if these side channels flowed all year round. In other words, the annual total needs to be distributed more evenly between the wet and the dry season if side channels flow throughout the year than if they only flow seasonally.

This factor does not apply to single-channel river systems.

4.6 Influence of modifying factors on the annual maintenance high-flow requirement

It is proposed that sites which, due to their physical and biological characteristics, are more susceptible to the primary impacts resulting from a reduction in high-flow events, will require a relatively greater proportion of their natural flow to serve as a "buffer" against these impacts. The following is an attempt to conceptualise the effect of the identified modifying factors on the high-flow requirement. Although these modifying factors influence the magnitude, duration, timing and frequency of individual high-flow events, these factors ultimately influence the annual high-flow requirement as well.

4.6.1 Factors influencing the susceptibility to reduced flood plain inundation

The modifying factor associated with this primary impact is the *valley type* within which the site is situated.

Valley type (presence/absence of flood plain)

It is hypothesized that the annual maintenance high-flow requirement will be greater at sites located in flood plains than in those located in more confined valley segments.

Flood plains sites are expected to have higher requirements due to the increased volume of water needed to inundate the plain and meet the greater water requirements of a wide belt of riparian vegetation. This is, however, a very coarse level of categorization as it ignores differences in high-flow requirements between gorge areas and less confined sites, as well as between flood plains of different sizes.

4.6.2 Factors influencing the susceptibility to reduced sediment mobilization

High-flow reduction is generally considered to result in a reduction in the river's ability to mobilize sediments. This impact, and the associated high-flow requirement is, however, modified by the *catchment sediment yield.*

Catchment sediment yield (high/low catchment sediment input)

It is hypothesized that the annual maintenance high flow requirement will be greater for rivers which are located in catchments which have a high sediment input than in catchments which have a low sediment input.

A greater volume of high flow is presumably required in high sediment yielding catchments in order to mobilize and flush sediments and, thereby, maintain channel shape.

4.6.3 Factors Influencing the susceptibility to reduced activation of seasonal channels and pools

The susceptibility of a site to reduced activation of seasonal channels and pools is obviously influenced by whether or not these channels and pools are present. Therefore, the *channel pattern* modifies the high-flow requirement.

Channel pattern (presence/absence of temporary pools and side channels)

It is hypothesized that the annual maintenance high flow requirement will be greater for sites which have temporary pools and side channels which are dependent on high flow events to be activated or recharged.

If no temporary pools or side channels are present, then the volume that is usually stipulated to activate these areas falls away and the annual flow requirement decreases.

4.6.4 Factors influencing the susceptibility to riparian vegetation “stress”

A reduction in high flows impacts on the riparian vegetation by reducing the *habitat* available for seedling establishment and by reducing the *connectivity* between the active channel and the subsurface water. Differences between sites in terms of the type of vegetation and the geology of the channel system influence the susceptibility of the site to riparian vegetation stresses and, hence, also the high-flow requirement.

Habitat requirements (presence/absence of bedrock-dependent species)

It is hypothesized that sites which have riparian vegetation which is dependent on the presence of bedrock patches will have relatively greater annual maintenance high-flow requirements than sites where riparian vegetation is established in alluvial sediments.

Certain riparian vegetation species require bedrock patches to establish themselves on. To maintain the availability of these patches, it is necessary to have more frequent high flows designed to flush sediments out of the system. This high flow requirement falls away at sites where the riparian vegetation is established in alluvial sediments.

Connectivity of active channel and subsurface water (poor/good)

It is hypothesized that sites at which connectivity between the active channel and the subsurface water is poor will have a relatively greater annual maintenance highflow requirement than sites where this connectivity is good.

Poor connectivity is generally associated with bedrock channels. Under these circumstances the water available for uptake by riparian vegetation can only be obtained directly from the flow in the channel or from isolated aquifers. It is, therefore, critical to the survival of the vegetation that these aquifers are periodically recharged. Due to the lack of lateral connectivity between the active channel and these isolated aquifers this means that high flows are required which are of sufficient magnitude to overtop the banks and reach the aquifers. In comparison, the recharge of subsurface water levels in alluvial channels doesn't require banks to be overtopped as connectivity between the active channel and the subsurface water is good.

4.7 Development of an "Eco-Logical" scoring system

Having identified ecological factors which potentially influence the IFR, and generated hypotheses on their individual effects, a pragmatic method has been developed to quantify the influence of the integrated set of physical and biological variables on the IFR at any site. The lack of scientific knowledge surrounding the relationships between the identified variables and the IFR components has meant that a purely logical approach needs to be adopted when quantifying the effect of each factor on the IFR. **It therefore needs to be stressed that the method is at this stage is still largely conceptual and should NOT be applied indiscriminately. It requires review and testing by a range of instream flow assessment specialists to determine its value as a rapid desktop IFR estimation procedure.**

The following premises underlie the proposed method:

- Past IFR workshop results reflect both the hydrological and ecological characteristics of the sites. Therefore, the hydrological curves constructed from past IFR results - and used in ***RESDSS*** to provide a desktop estimate of the instream flow requirements - can be considered to reflect the mean physical and biological characteristics of the sites used in the initial study. These are considered to be the *"ecological reference conditions"*.

- The instream flow requirement which is associated with the *reference condition* (and obtained from the hydrological curve) serves as a reference IFR. (Refer to Figure 4.1 where the bold line indicates the reference IFR for B-class rivers)

- A difference in any of the relevant *reference condition characteristics* will modify the reference IFR as hypothesized in Sections 4.4 to 4.6.

- This modification can be described quantitatively as the percentage by which the annual reference IFR should increase or decrease or, as the percentage by which the reference seasonal distribution should be steepened or flattened (% adjustment). For example, if the reference annual maintenance low-flow requirement is 20% MAR, and the % adjustment suggested for a certain factor is +5%, then the refined IFR will be 21% MAR.

- Primary impact variables and modifying factors will vary in the degree to which they modify the reference IFR. This variation can be expressed as a hierarchy of variables and factors which have a decreasing modifying influence on the reference IFR. Their relative "importance" can be described numerically by a set of *"impact-"* and *"category-weightings"*. (Described in more detail in section 4.7.2 and 4.7.3).

- Every physical or biological characteristic has an associated *"impact-"* and *"category-weighting"*. The modification to the reference IFR attributed to any single characteristic (in terms of %

adjustment) can be determined by the product of the two weightings.

- ❑ Summing the individual influences of all the relevant physical and biological characteristics which describe a particular site, results in an final percentage adjustment (*"score"*) that reflects the integrated effect of all relevant ecological factors on the reference IFR.
- ❑ Incorporating this percentage adjustment for each component into the IFR estimated by ***RESDSS*** results in a refined IFR which takes into account both hydrological, ecological and management class differences.

These premises have served as the foundation for the development of an "eco-logical scoring system" to quantify the influence of ecological modifying factors on the reference IFR. What follows is a description of the characteristics established as the reference condition, and an explanation of the "impact-" and "category-weightings" and the resultant "scores". The method by which the percentage adjustment to the reference IFR is obtained, using this scoring system, will be described in Section 4.8.

4.7.1 Ecological reference characteristics

The following physical and biological characteristics have been established as the "ecological reference condition" upon which the reference IFR is based:

- Summer rainfall region river
- Not shallow enough to influence temperature significantly
- Not slow enough to influence temperature significantly
- Unshaded channel
- Single channel
- Rectangular cross-sectional channel shape
- Alluvial channel
- Smooth channel bed (sand/gravel)
- Relatively steep river gradient
- Relatively high width:depth ratio
- High catchment sediment yield
- Relatively fine sediment grain size
- Low flows insignificant in terms of suspended sediment transport
- Significant seasonal riparian water requirement
- Establishment of riparian vegetation not dependent on bedrock patches
- Good connectivity between active channel flow and subsurface water
- No flood plain
- Marginal habitat a relatively significant biotope
- Instream habitat a relatively insignificant biotope
- No large mammals and reptiles present
- No large migratory fish and eels
- Temporary refuge areas available for biota during droughts

A variation in any of these characteristics is contended to influence the instream flow requirement.

4.7.2 Impact-weightings

The relative modifying influence of the primary impact variables on the IFR is described numerically by the "impact-weighting". The different weightings are based on the premise that the severity of the secondary biological and geomorphological impacts resulting from a reduction in flows are not the same for all of the primary impacts. In other words, it is assumed that, for example, the biological consequences of a change in temperature are relatively less severe than those resulting from a loss of habitat. Habitat is assumed to have a greater modifying potential than temperature and is given a higher impact-weighting. The greater the value of the weighting, the greater the importance of the impact relative to the other primary impact variables. At this point, the hierarchy of primary impact variables and the associated impact-weighting values have been based on what appears to be logical and reasonable. **These should not be considered to be the final weightings; values can easily be modified as more information and understanding becomes available.** The initial impact-weighting for each of the primary impacts is given in Table 4.4.

Table 4.4 Proposed hierarchy of primary impact variables and modifying factors in terms of their decreasing influence on the IFR components. (* and ~ indicate factors which are considered to have the same influence within the separate hierarchies.)

IFR Component	Proposed Hierarchy of Primary Impact Variables (Decreasing influence on IFR components)	Initial Impact-Weightings	Proposed Hierarchy of Modifying Factors (Decreasing influence on Primary Impact Variable) and their Category-Weightings
Annual Maintenance Low Flow	Marginal Habitat	5	Significance as a biotope Cross-sectional channel shape* Channel pattern* Seasonality of side channels
	Instream Habitat	5	Significance as a biotope Cross-sectional channel shape Channel roughness* Gradient* Channel pattern*
	Available Water	5	Significant riparian water requirement Channel type* Channel pattern*
	TSS Transport Capacity	4	Low flows significant for TSS transport* Catchment sediment yield* Input sediment grain size~ Local gradient~ Width:depth ratio~ Substrate~
	Temperature	3	Season of lowest flows Channel shading* Depth* Velocity*

IFR Component	Proposed Hierarchy of Primary Impact Variables (Decreasing influence on IFR components)	Initial Impact-Weightings	Proposed Hierarchy of Modifying Factors (Decreasing influence on Primary Impact Variable) and their Category-Weightings
Annual Drought Low Flow	Available Water	6	Significant riparian water requirement Channel type* Channel pattern*
	Marginal Habitat	5	Significance as a biotope Cross-sectional channel shape* Channel pattern* Seasonality of side channels~ Refuge areas~
	Instream Habitat	5	Significance as a biotope Cross-sectional channel shape Channel roughness* Local gradient* Channel pattern* Refuge areas*
	Temperature	4	Season of lowest flows Channel shading* Depth* Velocity*
Maintenance Low Flow Seasonal Distribution	Riparian Vegetation	5	Riparian water requirement
	Sediment Transport	5	Wet season sediment input
	Instream Habitat	3	Large mammals and reptiles
	Migration	3	Migratory species
	Secondary Channels	3	Type of flow
Annual Maintenance High Flow	Flood Plain Inundation	15	Valley type
	Sediment Mobilisation	15	Catchment sediment yield
	Activation of Seasonal Channels and Pools	5	Channel pattern
	Riparian Vegetation	5	Habitat requirements* Connectivity*

4.7.3 Category-weightings

The magnitude by which the IFR is modified, as well as the "direction" in which this modification occurs (ie. whether the reference IFR will increase, decrease or stay the same) is described by the weighting given to each classification category. The differences in magnitude between the categories associated with different modifying factors reflects the relative importance of each modifying factor in terms of its influence on the primary impact variables.

The values which are currently used in the program have been derived through an iterative process, in conjunction with the impact-weighting values, and taking into account the reference condition characteristics. While these values are inherent in the computer program and not visible to the user, it is possible to refine the category-weightings on the basis of a qualitative description of how, in relative terms, a modifying factor and its associated categories influences the IFR.

4.7.4 Scores

Any described characteristic is automatically linked to an impact- and category- weighting. For example, multi-thread channels have a category-weighting reflecting the influence of this characteristic on the IFR. As channel pattern is a factor modifying the impact of flow reduction on the marginal habitat, this characteristic is also described by the relevant impact-weight given to "marginal habitat". The product of the two weightings gives the percentage adjustment associated with any modifying factor ("factor score"). The sum of the factor scores for all factors modifying a primary impact is reflected by the "impact score". The "component score" is the total percentage adjustment suggested for each IFR component and is the sum of all the relevant impact scores. The component score reflects the integrated effects of all physical and biological characteristics which are assumed to modify that IFR component. In the case of annual flow requirements, a negative score reflects a suggested decrease in the total flow requirement. On the other hand, a negative value associated with the seasonal distribution is interpreted as a "flattening" of the seasonal distribution.

The current range of component scores is provided in Table 4.5. These ranges are currently set on the basis of what seems "reasonable". However, it is expected that this range will need to be modified for the individual components as more IFR data becomes available.

Table 4.5 Current range of component scores suggested for each of the individual IFR components.

IFR Component	**Maximum Percentage Decrease (% Decrease in Reference IFR)**	**Maximum Percentage Increase (% Increase in Reference IFR)**
Maintenance Low Flow : Annual Total	-15%	21%
Drought Low Flow : Annual Total	-6%	22%
Maintenance Low Flow : Seasonal Distribution	-16%	19%
Maintenance High Flow : Annual Total	-15%	25%

The scoring system hinges on the ability to identify which classification category best describes each of the relevant modifying factors at the site or section affected by a flow reduction. Its usefulness, in terms of providing meaningful results, depends on the accuracy of the hypothesized influence of each modifying factor (and classification category) and how accurately the impact- and category-weightings reflect the relative "importance" of each of the primary impact variables and modifying factors.

4.8 User guidelines for the "Eco-Logical" scoring system

The "eco-logical scoring system" has been written as a computer program using the DELPHI language and as such also functions as a decision support system. It has been designed to be incorporated into the ***RESDSS*** program to provide the possibility of refining site-specific desktop Reserve estimates by taking account of the influence of ecological differences between sites which are otherwise hydrologically similar. The program (***ECSCORE***) allows users to define the relevant physical and biological characteristics of the site by answering a series of questions pertaining to the primary impacts and modifying factors associated with each of the IFR components. It has, however, been structured to allow users to determine the percentage adjustment for one IFR component at a time. This involves three "steps" which are summarized in Figure 9.1 and which are explained in more detail below.

Step One:
The first step of the program lists the various IFR components for which an ecological refinement has, to date, been developed (Maintenance Low Flow: Annual Total; Drought Low Flow: Annual Total; Maintenance Low Flow: Seasonal Distribution; Maintenance High Flow: Annual Total). This list also indicates the current total adjustment (as a percentage increase/decrease to the reference IFR) suggested for each component (component score). Checking any one of the components calls up a second list of the associated primary impact variables.

Step Two:
Step two lists the primary impact variables associated with the selected component, along with their impact-weightings and the percentage adjustment which is attributed to that variable (impact score). Double-clicking on any item in the second list calls up a closable text box which provides a brief explanation of the relevant variable and its modifying factors.

Step Three:
A series of questions are called up in a third list as each primary impact variable in the second list is selected in turn. These questions ask the user to define which category of modifying factor best describes the site or river section affected by the flow reduction. These are answered "yes" by clicking on the check-box. An empty check-box automatically assumes that the answer to the question is "no".

In order to generate a total component score which is fully reflective of the site's relevant physical and biological characteristics, the questions posed in the third list need to be answered for each of the variables given in the second list. An asterix (*) appears alongside the impact variable once its associated questions have been answered, allowing users to easily see which variables still need to be described. An arrow (>) points to the primary impact under current consideration. The effect of each question on the IFR can be seen in the automatic adjustment of both the component score and impact score in steps one and two respectively.

Once a site description has been carried out, the user has the option of storing and/or printing the results and details of the assessment. A database has been set up within the DSS to store the component scores. This allows for easy comparison of the ecological adjustments suggested for each component at all of the sites. For each ecological assessment, the user has the option of saving the results as a new database record or, in the case of a refinement to a previous assessment, of saving the refined scores to an existing record. A set of shortcut keys are available which allow the user to move around the database: add, edit or delete records and refresh scores.

It is expected that the initial site assessments be refined as more or better ecological information becomes available for any site. Provided the results of the initial assessment have been stored in the database, it is possible to call up the initial site description by selecting "Restore Scores" from the "Data" menu and then loading the appropriate record from the database. This allows the user to refine only those characteristics for which better information is now available without having to go through the whole site description and scoring system again.

The printout for any site assessment contains the name of the site; the IFR components; the component scores; the primary impacts and their impact-weightings and impact scores and the questions and answers associated with each impact. An example of a typical printout is shown in Table 9.1. Selecting the "Print" menu allows the user to enter a title for the printout. The default title for records stored in the database gives the river and site name as specified in the database.

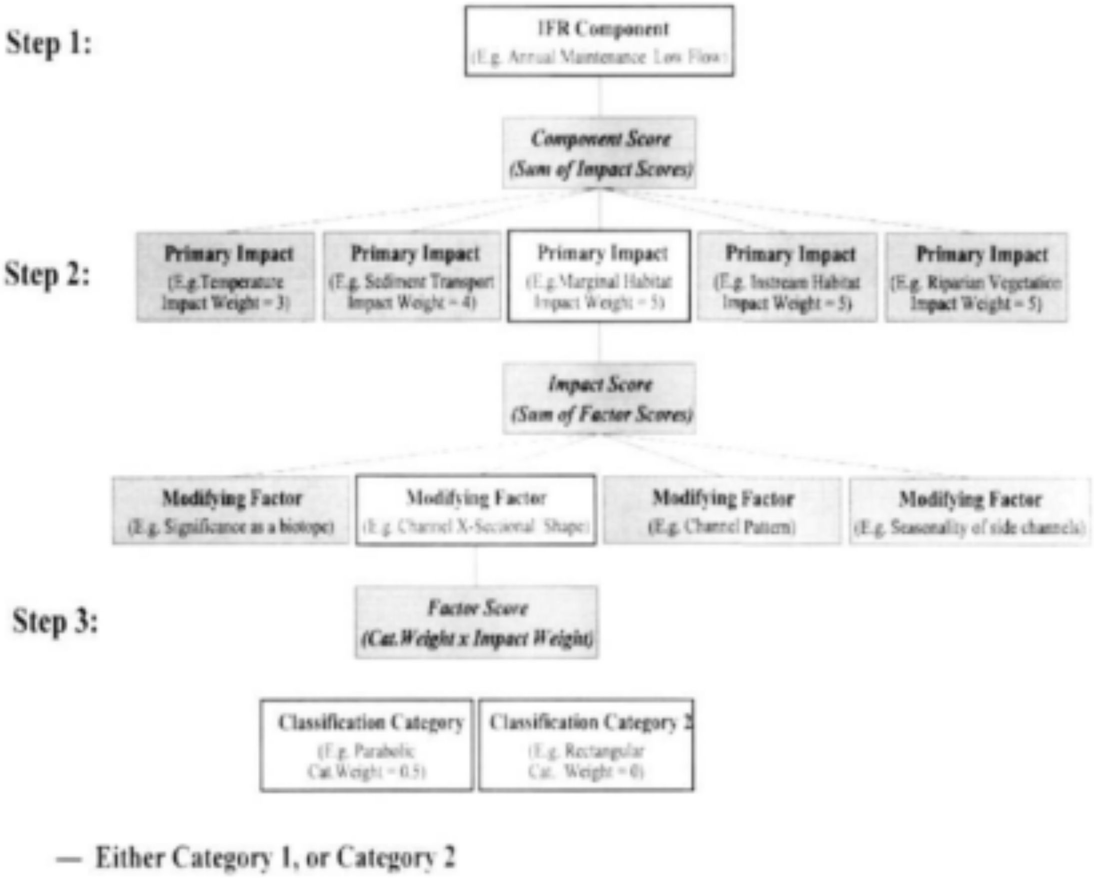


Figure 4.4 Structure of the "Eco-Logical" scoring system.

Table 4.6 Example of the summary printout of the site description and results of applying the “Eco-Logical scoring system” to a site reflecting the ecological reference conditions.

```
Summary of ecological factors scores for:
Ecological Reference Condition

IFR Component and score : Maint. Low Flow : Annual Total            0.00

     Temperature                            : Weight =   3.00 : Value =   0.00
         Dry season in summer ?                                   :  No
         Shallow enough to affect temp. significantly ?           :  No
         Slow enough to affect temperature significantly ?        :  No
         Channel shaded in the summer ?                           :  No

     Marginal Habitat                       : Weight =   5.00 : Value =   0.00
         Marginal habitat an important biotope ?                  : Yes
         Parabolic X-sectional channel shape ?                    :  No
         Multi-thread channel pattern ?                           :  No
         Perennial side channels present naturally ?              :  No


    Instream Habitat                      : Weight =   5.00 : Value =   0.00
         Instream habitat an important biotope ?                  :  No
         Rectangular  X-sectional channel shape ?                 : Yes
         Single channel ?                                         : Yes
         Rough (cobble) channel bed ?                             :  No
         Steep gradient ?                                         : Yes

    Riparian Vegetation                   : Weight =   5.00 : Value =   0.00
         Significant riparian water requirement ?                 : Yes
         Bedrock channel ?                                        :  No
         Multi-thread channel ?                                   :  No

    TSS Transport Capacity                  : Weight =   4.00 : Value =   0.00
         Low flows significant for sediment transport ?           :  No
         High catchment sediment yield ?                          : Yes
         Coarse input sediment grain size ?                       :  No
         Low gradient ?                                           :  No
         Low width:depth ratio (narrow & deep) ?                  :  No
         Cobble bed ?                                             :  No

IFR Component and score : Drought Low Flow : Annual Total           0.00

    Temperature                             : Weight =   4.00 : Value =   0.00
         Dry season in summer ?                                   :  No
         Shallow enough to affect temp. significantly ?           :  No
         Slow enough to affect temperature significantly ?        :  No
         Channel shaded in the summer ?                           :  No

    Marginal Habitat                      : Weight =   5.00 : Value =   0.00
         Marginal habitat an important biotope ?                  : Yes
```

```
         Parabolic X-sectional channel shape ?                  :  No
         Multi-thread channel pattern ?                         :  No
         Perennial side channels present naturally ?            :  No
         Temporary refuge areas available for biota ?           : Yes



    Instream Habitat                    : Weight =   5.00 : Value =   0.00
         Instream habitat an important biotope ?                :  No
         Rectangular  X-sectional channel shape ?               : Yes
         Single channel ?                                       : Yes
         Rough (cobble) channel bed ?                           :  No
         Steep gradient ?                                       : Yes
         Temporary refuge areas available for biota ?           : Yes

    Riparian Vegetation                 : Weight =   6.00 : Value =  -0.60
         Significant riparian water requirement ?               : Yes
         Bedrock channel ?                                      :  No
         Multi-thread channel ?                                 :  No

IFR Component and score : Maint. Low Flow : Seasonal Dist.           0.00

    Riparian Vegetation                  : Weight =  10.00 : Value =   0.00
         Is year round water necessary for survival ?           :  No

    Instream Habitat                     : Weight =   6.00 : Value =   0.00
         Large mammals and reptiles present ?                   :  No

    Sediment Transport                   : Weight =  10.00 : Value =   0.00
         Wet season flows facilitate transport of TSS ?         :  No

    Migration                            : Weight =   6.00 : Value =   0.00
         Wet season flows facilitate fish & eel migration ?     :  No

    Secondary Channels/Distributaries   : Weight =   6.00 : Value =   0.00
         Seasonal side channels ?                               :  No

IFR Component and score : Maint. High Flow : Annual Total         0.00

    Floodplain Inundation                : Weight =  15.00 : Value =   0.00
         Presence of flood plain ?                              :  No

    Sediment Mobilisation               : Weight =  15.00 : Value =   0.00
         High sediment input ?                                  : Yes

    Activation of Seasonal Channels and Pools:Weight = 5.00 : Value =   0.00
         Presence of temporary pools and side channels ?        :  No

    Riparian Vegetation                  : Weight =   5.00 : Value =   0.00
       Vegetation established on bedrock patches ?            :  No
       Subsurface water and channel flow poorly connected ?   :  No
```

4.8.1 Preliminary testing of scoring system

This "eco-logical" scoring system is available to be distributed to a number of river scientists for testing on rivers for which both ecological and IFR data are available. Results of these tests will be included in updated versions of this document and posted on the IWR web page.

4.8.2 Potential refinement of ecological factors and scores

As this is very much a first attempt at quantifying the influence of ecological characteristics on the instream flow requirement, it is expected that current factors and weightings will need to be refined in future as more information becomes available. The "eco-logical" scoring system is designed to be flexible enough to add additional modifying factors (or take out insignificant and irrelevant ones) and to change the magnitude and/or direction of the modification associated with each factor.

4.9 Conclusions and recommendations

This sub-project was initiated to investigate the potential for incorporating ecological considerations into the hydrologically-based decision support system developed to provide initial, low-confidence, quaternary-catchment scale, desktop IFR estimates for Ecological Reserve planning purposes (***RESDSS*** as described in Hughes & Münster, 1999). The result has been the development of an "eco-logical" scoring system which will, if found to be acceptable by instream flow assessment specialists, provide a practical method for quantifying the degree to which the reference IFR estimated by ***RESDSS*** should be refined in order to take into account those physical and biological differences between IFR sites which are considered to influence the IFR.

The choice of relevant "modifying factors" has been based on considerations of which physical and biological characteristics will significantly influence the severity of impacts to the integrity of the river ecosystem resulting from a reduction in flows. The underlying assumption is that sites with characteristics which "buffer" the ecosystem against the negative impacts of flow reduction, or changes to the seasonal flow regime, will have lower flow requirements than sites which are more susceptible to these impacts. The "eco-logical" scoring system has been based on ordering these impacts and the physical and biological factors hierarchically, and weighting them to reflect their relative and absolute influence on the IFR.

Owing to the inability to generalize or extrapolate ecological characteristics to describe entire quaternary catchments, it is not possible to use this scoring system to refine Reserve desktop estimates conducted at the national level. However, it is expected that these initial low-confidence IFR estimates can be improved if the scoring system is applied to ecologically-sensitive sites within the catchment and for which the required physical and biological data is available or obtainable from a rapid site visit. The resultant refinement to the desktop estimate is expected to give a value whose accuracy lies somewhere between that of the desktop Reserve estimate and the rapid determination Reserve estimate. This estimate may in future be referred to as the "eco-logical desktop estimate".

The constraints of limited scientific data has meant that the identification of relevant modifying factors and the development of the scoring system, has been based on a conceptualised understanding of the ecological factors and mechanisms influencing instream flow requirements. This, unfortunately, reduces the confidence in the accuracy of the results. However, a decision needs to be taken as to whether desktop-level IFR estimates should be based purely on the hydrological variation between rivers, or whether it is preferable to allow for some modification to the reference IFR to reflect the site-specific physical and biological characteristics influencing the IFR as well - even if these modifications are initially based purely on a logical "best-guess". It is, however, hoped that the approach used in the scoring system will encourage future research to focus on the mechanistic relationships between ecological characteristics and the instream flow requirements so that the results of these studies can be used to refine the factors and weightings currently included in the scoring system.

In practice, the approach would be applied by a limited number of specialists who have a reasonable knowledge of the specific river site in terms of the availability and quality of the habitat for different biota.

5. REAL -TIME OPERATION OF THE RESERVE

Sections 2 and 3 of this report referred to the different methods that can be used to design a representative time series of ecological flow requirements: one based on a daily time step that differentiates between low and high flows and one based on a monthly time step that only generates the volumetric requirements. The daily time step approach is based on the IFR model developed by Hughes et al. (1997) which was originally designed to be at least partially applicable to the real-time operation of the reserve. The model essentially manipulates the daily time series of flows either measured, or simulated, at a reference site that is considered to have a flow regime suitable for providing the climatic signals that are required to differentiate between times when there would naturally be plenty of water available and during times of drought. The flow-time series is used in the model with the sites-flow duration curve information and a set of calibrated ‘rules’ to determine the ecological flows required on a daily basis. There are a separate set of rules and model algorithms for the low and high flows and while the low-flow algorithms are straightforward to apply in real-time, the high-flows are not because of the need to project in terms of time in order to predict future high-flow event conditions.

If the same (or similar) principles are to be applied in real-time operation, the model and the rules have to be calibrated using a reference flow-time series for a site where ongoing daily streamflow gauging can take place. These gauged flows would then be passed to the operational centre in near real-time, where they would be used to update the model simulations and generate the ecological requirements. These requirements would then be used with other techniques (including flow routing models, supply and demand control models) to operate the system through either reservoir releases, abstraction control or a combination of the two.

A Delphi program is being developed to perform all the required low-flow functions of the IFR model for operational use in the Sabie/Sand system where the control of high flows is not really possible due to the relatively small proportion of the catchment that is controlled by reservoir storages.

5.1 A prototype program for real time implementation of the low flow component

One of the initial considerations when designing the program was that in many cases there will not be an existing flow gauging station that is suitable for calibrating the IFR model prior to the implementation of the scheme. This suggests that a simulated flow time series (using an appropriate rainfall-runoff model or similar tool - see section 2.1.1) will be required to establish the model and carry out the initial calibrations. While it is possible that such simulations could continue to be made into the future using real-time inputs of rainfall (and other hydrometeorological data), it is considered more likely that some form of gauging station will be established for real-time determination of the ecological requirements. This is the planned approach for the Sabie/Sand system and it is expected that two such sites will be established, one each in the Sabie and Sand Rivers. The historical time-series information used to establish the IFR model at a specific site and the real-time data that the model will use for future estimations could be different, to a lesser or greater degree, due to the inherent inaccuracies in any simulation model. This implies that the IFR model may need to be recalibrated once a suitable amount of observed data have been collected and it suggests further that the software should include all the facilities that are required. However, it is unlikely that the responsibility for that re-calibration will be given to the operator and, therefore, the design and calibration functions need to be password-protected from the operational functions. Figure 5.1 illustrates the front page of the prototype program after the details for Sabie Site 4 have been loaded and the calibration option selected.

The ‘Select Site’ site button is used to access different ‘*.ini’ files which are text files that contain site-specific reference information related to data files or parameter values. An example is provided below with explanations of the meaning of the contents of the file, where the bold type are the fixed program references and the non-bold components are set by the user.


At : Sabie IFR Site 4

Welcome to the routines for setting Instream Flow Requirements

At : Sabie IFR Site 4

Developed by the IWR, Rhodes University

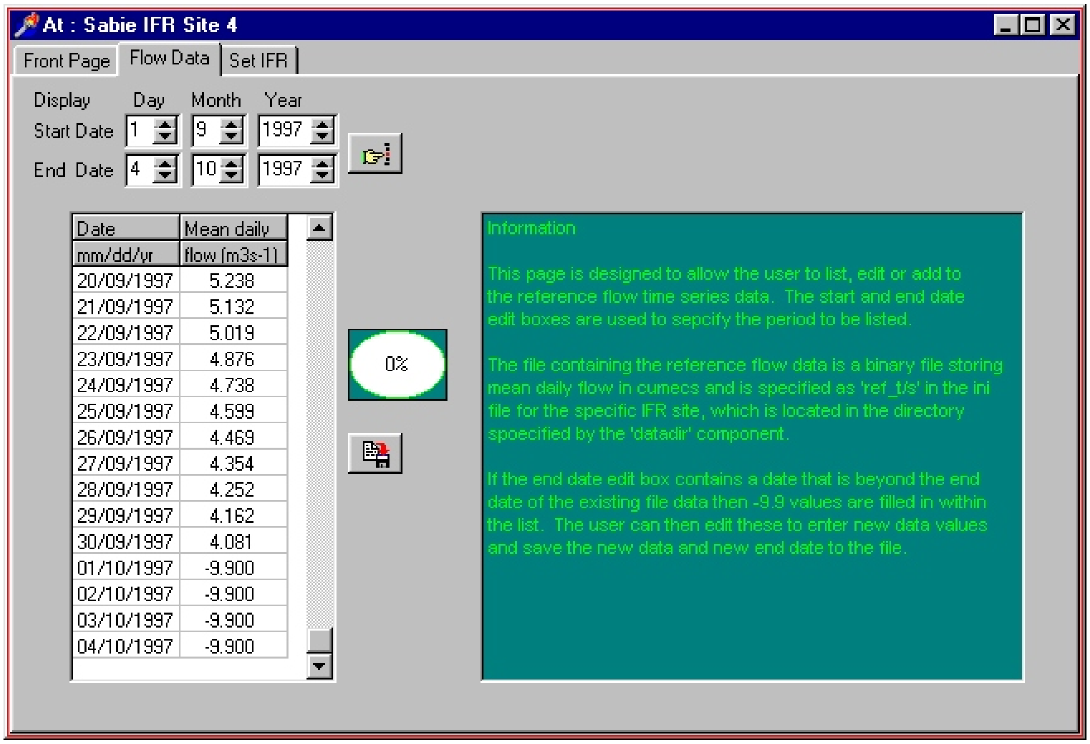
Figure 5.1 Front page (starting screen) of the prototype operational program to determine ecological flow requirements.

[startup]	
text=Sabie IFR Site 4	Name of the site and used in the program header.
datadir=c:\ifrcont\data\	Directory containing all relevant data files.
ref_t/s=sabieref.ts1	Binary data file containing the reference flow-time series.
ifr_t/s=sabieifr.ts1	Binary data file containing the ecological requirements.
dc_data=sabiedc.dat	Text data file containing the duration curve data (see later).
ifr_rules=sabrule.par	Text data file containing the rule data.
image=mei92.bmp	Bitmap file containing the front page bitmap photograph.
Bfparam=0.985	Default baseflow parameter (see later).

Figure 5.1 illustrates that there are two options: ‘Operation’ (the default) and ‘Calibration’. If the “operation” option is selected, then the last three page tags (D. Curve, IFR Rules and Update T/S) are not shown and the facilities associated with them cannot be used. The details of the five different function pages are provided below.

5.1.1 Flow data page

This is the page that is used by the operator to update and edit the flow data at the reference gauge site (or in some circumstances it may be a model simulation site). In the specific example used in figure 5.2 the existing data (1952 to October 1997) have been derived from a daily rainfall-runoff model calibrated at the site where a new gauging station is to be constructed. Before final use of this program, it will be necessary to update the rainfall-runoff model simulations to the point in time at which the gauge becomes operational; thereafter which the gauged data can be added in real-time.



Display	Day	Month	Year
Start Date	1	9	1997
End Date	4	10	1997

Date mm/dd/yr	Mean daily flow (m3s-1)
20/09/1997	5.238
21/09/1997	5.132
22/09/1997	5.019
23/09/1997	4.876
24/09/1997	4.738
25/09/1997	4.599
26/09/1997	4.469
27/09/1997	4.354
28/09/1997	4.252
29/09/1997	4.162
30/09/1997	4.081
01/10/1997	-9.900
02/10/1997	-9.900
03/10/1997	-9.900
04/10/1997	-9.900

Information

This page is designed to allow the user to list, edit or add to the reference flow time series data. The start and end date edit boxes are used to sepcify the period to be listed.

The file containing the reference flow data is a binary file storing mean daily flow in cumecs and is specified as 'ref_t/s' in the ini file for the specific IFR site, which is located in the directory spoecified by the 'datadir' component.

If the end date edit box contains a date that is beyond the end date of the existing file data then -9.9 values are filled in within the list. The user can then edit these to enter new data values and save the new data and new end date to the file.

Figure 5.2 Flow data page used for entering and editing the reference flow data.

The user may set the start and end dates of the data to be displayed in the window below after the ‘Find Data’ button to the right is clicked. If the user selects an end date that is beyond the end date of information in the reference flow time series binary file, then those days are added to the list and populated with flow values of -9.9 (i.e. missing data). The user may now simply type in the values observed from the gauge and click the ‘Save Edits to File’ button immediately to the right.

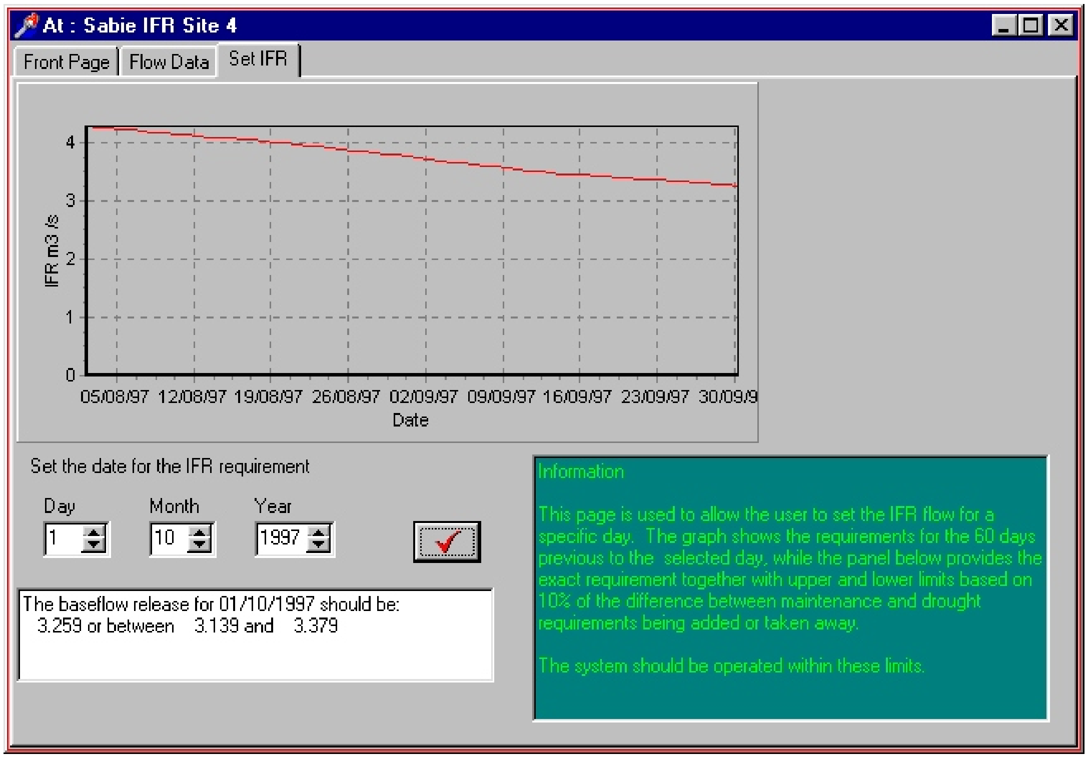
Saving the data to the reference flow file also runs the IFR model with the current default parameters or rules and updates the duration curve information as well as the file containing the daily ecological requirements.

5.1.2 Set IFR page

This page is used by the operator to define the low-flow ecological requirements on any day for which there are non-missing flow values in the reference flow-time series file. The screen displays the last 60 days of requirements so that the user can see the recent trend and decide whether it is necessary to adjust operating rules or whether the current operation will provide flows within the required tolerance. The tolerance is currently set on the basis of 10% of the difference between the defined maintenance and drought requirements. Further details can be added to this page after discussions with representatives of the users or as the necessity arises.

5.1.3 D.Curve page

This page (figure 5.4) is simply used to update the duration curve information and write it out to the text file specified by the dc_data parameter in the *.ini file. This facility is somewhat redundant as the duration curves are automatically re-calculated every time that data are added to the reference flow- time series file. It has been retained for the sake of completeness.



Set the date for the IFR requirement

Day: 1
Month: 10
Year: 1997

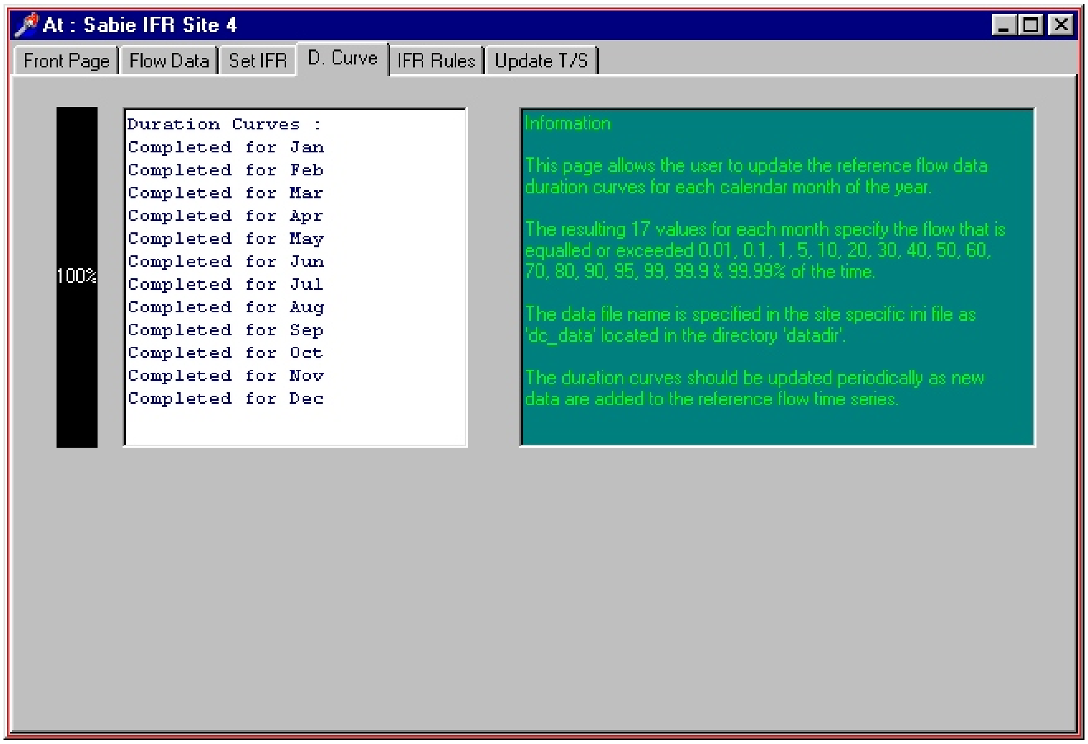
The baseflow release for 01/10/1997 should be:
3.259 or between 3.139 and 3.379

Information

This page is used to allow the user to set the IFR flow for a specific day. The graph shows the requirements for the 60 days previous to the selected day, while the panel below provides the exact requirement together with upper and lower limits based on 10% of the difference between maintenance and drought requirements being added or taken away.

The system should be operated within these limits.

Figure 5.3 Set IFR page used to display the requirements for the 60 days up to and including a user-specified date.



```
Duration Curves :
Completed for Jan
Completed for Feb
Completed for Mar
Completed for Apr
Completed for May
Completed for Jun
Completed for Jul
Completed for Aug
Completed for Sep
Completed for Oct
Completed for Nov
Completed for Dec
```

Information

This page allows the user to update the reference flow data duration curves for each calendar month of the year.

The resulting 17 values for each month specify the flow that is equalled or exceeded 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 & 99.99% of the time.

The data file name is specified in the site specific ini file as 'dc_data' located in the directory 'datadir'.

The duration curves should be updated periodically as new data are added to the reference flow time series.

Figure 5.4 D.Curve page used to update the flow duration curve data for the reference flow- time series.

5.1.4 IFR Rules page

This is the page (figure 5.5) that can be used if the IFR requirements are modified, or if the assurance rules need to be modified for any reason. The ‘parameter’ table includes five columns :

- MLIFR, or the maintenance low-flow requirement in $m^3 s^{-1}$ and taken directly from the results established at a reserve workshop.

- DLIFR, or the drought low-flow requirements in $m^3 s^{-1}$ and taken directly from the results established at a reserve workshop.

- MRULE, or the % point value used to fix the assurance level of maintenance flows.

- DRULE, or the % point value used (with MRULE) to determine the assurance levels of flows between maintenance and drought.

- M.MAX, or the % point differential value (below MRULE) used to determine, togther with MRULE, the extent to which flows above MLIFR are required.

Further explanation of these IFR model parameters are given in Hughes et al. (1997).

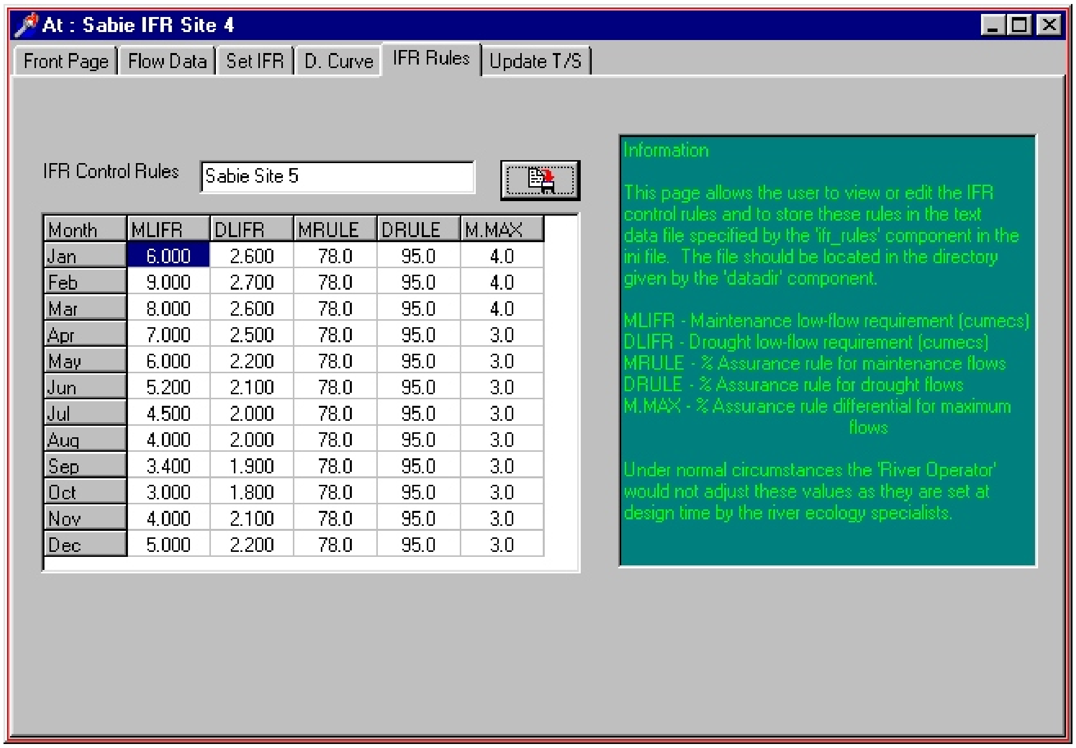
5.1.5 Update T/S page

This is the main page (figure 5.6) that is used for checking the IFR requirements and re-calibrating the IFR model (using the IFR Rules page to modify the parameters where necessary). The model has been modified slightly since the original version was published (Hughes et al., 1997), but the basic concepts remain the same. As in the previous version of the model, the daily reference flows are converted to % point equivalents on the flow duration curve. These are then inverted (100 - % points) to generate a time series of % values, where the highest values represent high flows and the lowest values, low flows. The new time-series is then subjected to a baseflow separation analysis (see Smakhtin and Watkins, 1997) using the value of the baseflow control parameter at the top of the screen. This value can be edited in the *.ini file after calibration, if necessary. Essentially, values close to 1.0 give a much flatter baseflow response that smaller values, which will generate a more peaked shape in the baseflows (and therefore, more values with high inverted % points).

The time-series of inverted % points are then compared with the rules given in columns 3, 4 and 5 of figure 5.5 to determine whether the ecological flow requirements on any day should be above maintenance, between maintenance and drought, or at drought levels. The final step is to carry out some simple interpolation between the flow requirements of adjacent months (columns 1 and 2 of figure 5.5) to generate a requirements time-series that is relatively smooth. The results are displayed graphically in the lower part of figure 5.6 which shows the reference flow time-series and the final requirements. The user can zoom in and pan within this graph and can expand it to fill the whole program window.

The text window at the top summarises the results on an annual basis using the percentage of time at drought as well as above and below maintenance levels. The design maintenance and drought annual volume requirements, as well as the final average annual volume are also provided. The 'Monthly On' button allows the user to bring up a monthly summary of the percentage of time that the flows were at drought levels and at or above maintenance levels for each month of the year. These data are useful for achieving similar assurance levels for individual months.

The reference flow and final requirement time series files are compatible with the TSOFT time series analysis and display software being developed by the IWR (Hughes et al., 1999) which can be used for further investigating the model results.



IFR Control Rules: Sabie Site 5

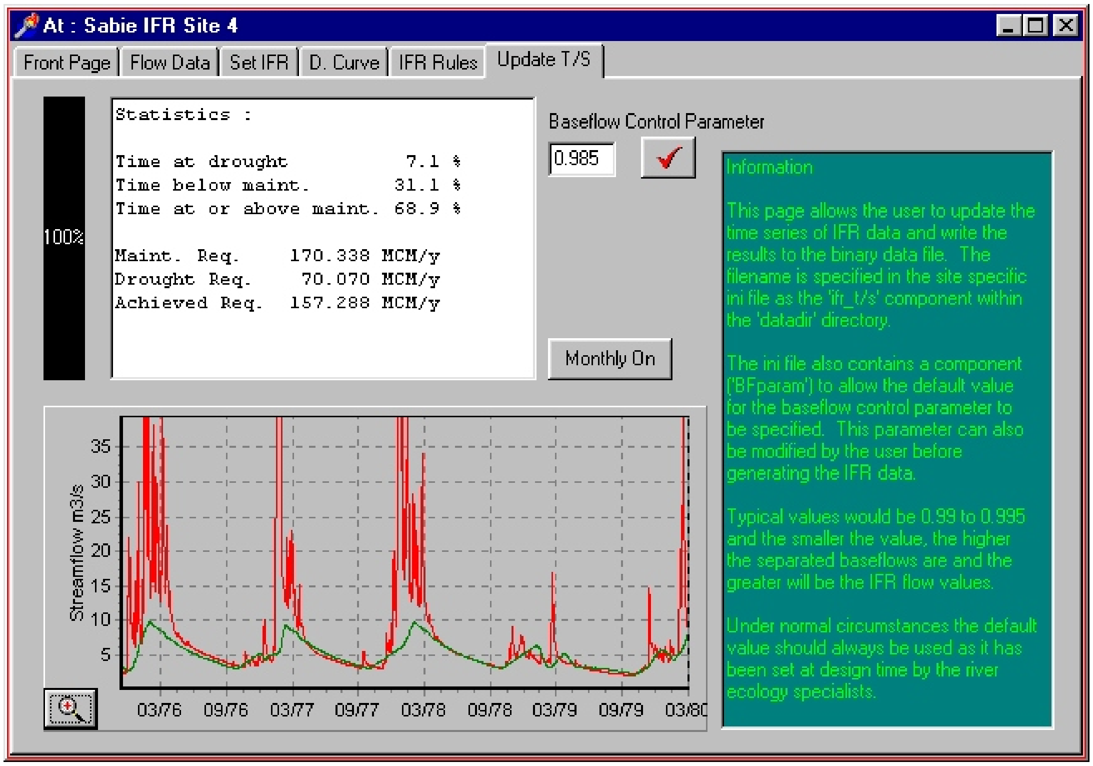
Month	MLIFR	DLIFR	MRULE	DRULE	M.MAX
Jan	6.000	2.600	78.0	95.0	4.0
Feb	9.000	2.700	78.0	95.0	4.0
Mar	8.000	2.600	78.0	95.0	4.0
Apr	7.000	2.500	78.0	95.0	3.0
May	6.000	2.200	78.0	95.0	3.0
Jun	5.200	2.100	78.0	95.0	3.0
Jul	4.500	2.000	78.0	95.0	3.0
Aug	4.000	2.000	78.0	95.0	3.0
Sep	3.400	1.900	78.0	95.0	3.0
Oct	3.000	1.800	78.0	95.0	3.0
Nov	4.000	2.100	78.0	95.0	3.0
Dec	5.000	2.200	78.0	95.0	3.0

This page allows the user to view or edit the IFR control rules and to store these rules in the text data file specified by the 'ifr_rules' component in the ini file. The file should be located in the directory given by the 'datadir' component.

MLIFR - Maintenance low-flow requirement (cumecs)
DLIFR - Drought low-flow requirement (cumecs)
MRULE - % Assurance rule for maintenance flows
DRULE - % Assurance rule for drought flows
M.MAX - % Assurance rule differential for maximum flows

Under normal circumstances the 'River Operator' would not adjust these values as they are set at design time by the river ecology specialists.

Figure 5.5 IFR Rules page used to edit the basic IFR requirements data and assurance rules.



```
Statistics :

Time at drought          7.1 %
Time below maint.       31.1 %
Time at or above maint. 68.9 %

Maint. Req.     170.338 MCM/y
Drought Req.     70.070 MCM/y
Achieved Req.   157.288 MCM/y
```

Baseflow Control Parameter: 0.985

This page allows the user to update the time series of IFR data and write the results to the binary data file. The filename is specified in the site specific ini file as the 'ifr_t/s' component within the 'datadir' directory.

The ini file also contains a component ('BFparam') to allow the default value for the baseflow control parameter to be specified. This parameter can also be modified by the user before generating the IFR data.

Typical values would be 0.99 to 0.995 and the smaller the value, the higher the separated baseflows are and the greater will be the IFR flow values.

Under normal circumstances the default value should always be used as it has been set at design time by the river ecology specialists.

Figure 5.6 Update T/S page used to run the IFR model and re-generate the time series of ecological flow requirements.

5.2 Use of the program output

All that the prototype program estimates is the ecological reserve requirement at the specified site. It does not attempt to estimate what will be required in terms of reservoir releases or alternative management practices to ensure that such a flow will be achieved at the site. To be able to estimate the management requirements and practices, at least some of the following will have to be taken into account by associated or linked methods :

❑ Natural losses (evaporative, seepage, etc.) in the channel from the point at which flow control is possible down to the IFR site.

❑ Abstraction losses from the channel down to the IFR site. This may involve issuing limitation or curtailment orders to abstractors at times of limited water availability.

❑ Attenuation of release rates during the movement through the channel system. This may not be an important issue in a continually-flowing system, where the flow control point and the IFR site are not too distant from each other, particularly as it is not important for the actual flow to vary with exactly the same time pattern as the model suggests (a delay of several days will not be important). However, in ephemeral or seasonal systems, this issue may become important at the start of a release when a substantial amount of channel pool storage may have to be catered for. It could also be relevant to multi-thread channels, where an increase in flow may give rise to the activation of elevated pools and a proportion of a release being lost to storage. This will be very important when floods or high flow requirements are considered, as a considerable degree of peak attenuation will occur in some situations. However, the prototype software only considers low flows at present. Some of the issues relating to high flows are discussed in the next section.

5.3 Operational problems associated with satisfying the ecological reserve high flow component

While the high-flow requirement generation procedures within the IFR model have already been used quite successfully at several IFR workshops, there are a number of limitations in the manner in which the workshop results can be interpreted and used within the model and an even greater number of limitations in terms of the use of the model for operational high-flow determination.

The first issue relates to the fact that the workshop participants frequently specify high-flow requirements in relatively complex ways that do not easily lend themselves to simple translation into computer-based rules. This is not a totally restrictive issue as the model can be increased in complexity, albeit at the expense of more complex and difficult-to-understand methods of setting up the rules.

The second issue is more difficult to resolve and relates to the fact that, while the low -low requirements are more or less continuous and are expected to be controlled by the relatively slowly changing baseflow response at the reference flow-site, the high flows are event-driven. Within the original model (designed to be used for design purposes with historical data series), the software can look forward in time to recognise events and queue high-flow ecological requirements accordingly. If the same approach were to be used in near real-time for operational purposes, a forecast would be required.

One of the reasons for attempting to match the high-flow requirements to real events is to match any artificial releases to natural downstream tributary inflows and reduce the volume of water that is required to be released. If there is no matching, either a greater volume of a valuable resource will be used up or the IFR site will be subject to a number of smaller events (some natural and some artificial) than is required by the IFR design. This is a situation that may need to be avoided as it may have serious consequences for channel maintenance.

Even if the IFR model was able to estimate satisfactorily the timing and magnitude of the required high- flow releases, there are still at least two further issues. One is that the peak-flow that has to be released from storage (if that is the mechanism of flow control) may have to be substantially greater than the IFR requirement to allow for attenuation in the downstream channel reach. This may have deleterious effects (related to channel erosion) immediately downstream of the release point. The other is that high rate release mechanisms in dam structures are extremely expensive and could increase the design and construction costs of new storage reservoirs dramatically. It has been frequently suggested that the very large high flows requested to deal with channel maintenance will occur anyway as the storage reservoir will be filled and spillage will take place. However, if dams with storage volumes exceeding a few hundred % of MAR are constructed , (note: Katse Dam in the Lesotho Highlands Project) this may well not be the case.

Clearly, these are issues that will have to be resolved before any high flow requirements can be implemented, but it is apparent that many compromises will have to be reached before a satisfactory and workable solution can be found.

6. CONCLUSIONS AND RECOMMENDATIONS

The original proposal for the project **'Integration and application of daily flow simulation approaches within Southern Africa'** only had a small component that was related to the development of IFR or Ecological Reserve methodology. However, the project was somewhat re-orientated during 1998 in response to DWAF's relatively urgent needs in terms of implementation of the new Water Act. The involvement of the project team in earlier IFR workshops had prompted the development of the IFR (Hughes et al., 1997) and DAMIFR (Hughes and Ziervogel, 1998) models, as well as further work on simple methods of estimating daily flow time series (Hughes and Smakhtin, 1996 and Smakhtin, 1999) as well as displaying and analysing time series data (Hughes et al., 1999). However, the new Reserve methodology required a range of approaches that not only included detailed studies (Comprehensive Reserve), similar to those already carried out, but also simpler and quicker methods that would be appropriate to the Desktop and Rapid Reserve approaches. One specific requirement was to develop an approach that would be able to populate the database underlying the National Water Balance Model with ecological Reserve estimates. This meant that a method had to be found for generating these estimates for all 1946 quaternary catchments in the country (including Lesotho and Swaziland). Methods based on daily flows would not have been appropriate as the data are not available nationwide. However, monthly time series of simulated naturalised streamflows are available and seemed appropriate. Hence, the methods discussed in sections 3 and 4 were developed using the methods that had already been developed for use with daily data as a base so that there is a measure of consistency of approach (and hopefully, results) between the different approaches. Section 5 represents a starting point for injecting more ecological signals into the methods which are believed to be currently too heavily based on hydrology and streamflow regime characteristics.

A great deal of time has been spent during this project, developing and applying techniques that are relevant to the determination of the Ecological Reserve. There are, however, two main issues that are outstanding. The first of these is that the links between the ecological functioning of rivers and the hydrological regime (streamflow variations at various time scales) are still not very clear. This places limits on the confidence in the results of Desktop or Rapid Reserve determinations, mainly because these are almost totally based on hydrological information. The second is the fact that the tools that are available (either developed by this project, within the IWR by other projects, or by other institutions) are neither integrated into a common package (some are still in DOS format, while others are Windows-based programs), nor are they readily usable by a wide group of individuals. The latter point could be addressed through a series of training programmes, but the former is less easy to address in the short- term and requires some further development of integrating software.

The main recommendations stemming from this component of the project are that the available tools should be better integrated and that more practitioners need to be trained in their use. These are not independent of each other and the development of more integrated tools will facilitate the training of specialists in this field.

The Institute for Water Research and the Freshwater Studies Unit at the University of Cape Town have recently collaborated on the compilation of research proposals to the Water Research Commission to carry out a series of projects related to the determinations of the Ecological Reserve. One of these projects is designed to integrate the water quality aspects of the Reserve into the whole process. A further proposal was submitted by the Centre for Water in the Environment at the University of the Witwatersrand on the developments of methods for carrying out hydraulic analyses for Reserve determinations. The IWRs contributions (apart from the water quality project referred to above) can be summarised in the following overall aim :

> To develop a consistent protocol for the quantification of the Ecological Reserve within a risk-based framework.

Three specific objectives have also been identified and are designed to address some of the issues that were raised during the current project and highlighted above :

> To design and program a decision support system (DSS) which will eventually accommodate all the steps and procedures required for quantifying the Ecological Reserve.
>
> To develop a risk-based process for the assessment of the water quantity aspects of the Ecological Reserve, by combining biotic stress-response relationships with streamflow time series.
>
> To further understand the ecological conditions which require different flow regimes for their functioning.

One part of the DSS component is designed to put together new and existing tools into a much more integrated framework that will make them easier to use and more accessible to a wide range of potential users. A great deal of the groundwork has already been carried out during the current project, which should allow the new project to progress rapidly.

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