DEVELOPMENT OF A REVISED DESKTOP MODEL FOR THE DETERMINATION OF THE ECOLOGICAL RESERVE FOR RIVERS

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

The main objective of the project was to create a new version of the Desktop Reserve model that more explicitly includes the links and relationships between hydrology, hydraulics and ecological response. The previous version of the Reserve Desktop model, that has been in use for a number of years, was largely based on hydrology and regional model parameters that attempted to implicitly include variations in ecological response and the flow requirements needed to maintain different levels of ecological functioning. The parameters were largely based on regional differences in seasonal distributions of stream flow, flow duration curve characteristics and the degree of hydrological variability. The latter was used to estimate the annual proportions of natural mean annual runoff that would be required for low and high flows to maintain rivers in a specified ecological category (A to D). The natural seasonal distributions of total and separated baseflow were used to distribute these annual totals over the 12 months of the year, while the natural flow duration curve characteristics were used to specify the frequency (or assurance) characteristics that are necessary to ensure some similarity in temporal flow variability between the natural flows and the Reserve requirements.

Since the old Desktop Reserve model was designed, there have been many developments in the detailed methods used to set Reserves that are applied by specialists during workshops. One of the major developments was related to the flow stressor response methods, which essentially uses a knowledge of the hydraulic habitat requirements of river biota (fish, macro invertebrates and riparian vegetation, for example) linked to the hydraulic characteristics of a channel cross-section to specify the ecological stress conditions that will occur under different flow regimes. This information can then be used to specify what changes to the stress regimes can be considered acceptable for different levels of protection (Reserve categories A to D). The required stress regimes can then be converted to equivalent flow regime characteristics using the links between the hydraulics and the hydrology. The scientific basis of this approach has been presented in a number of reports and other publications and is summarized in Hughes and Louw (2010).

This report therefore explains the way in which the principles underlying the detailed flow stressor response methodology have been incorporated into a Revised Desktop Reserve Model (RDRM). The model has been implemented as part of both the previous SPATSIM software, as well as the new SPATSIM-HDSF framework. The model has been structured to take the user through the different steps of analyzing and estimating the data that are required for the integrated approach. The first step involves a hydrological sub-model, the second a hydraulic sub-model, the third an ecological sub-model, while the fourth and final steps represent the addition of high flow estimates and the integration of all the sub-models into the final estimates of the Reserve requirements. The report is structured in a similar way as the model. Chapter 1 provides some further details of the background to the model development, while Chapter 2 focuses on the links between hydrology, ecology and hydraulics. As one of the major components of the project was the development of the desktop hydraulics sub-model, this is dealt with in some detail in Chapter 3. Chapter 4 presents the details of the model and represents an initial draft of the user manual, while

Chapter 5 reports on some initial assessments of the model and Chapter 6 provides some conclusions and recommendations.

The purpose of the ecological model is to explicitly incorporate ecological aspects within the RDRM. The work undertaken during this study follows directly on from the existing project (K8/657) where the major focus has been to establish the principles and concepts of ecological similarity of sites and using filter models to identify the indicator species at approximately 800 fish sites in the country. The broad principles to specify habitat requirements (linked to the indicator species/groups, geozones and river width/size) were determined and tested on the cobble bed systems in the Komati River.

In terms of this WRC project, the initial approach that was decided on was to use aspects of the Fish Flow Habitat Assessment (FFHA) method for the ecological input into the RDRM. It was however indicated by Dr Kleynhans (pers comm, 2010), that the use of the FFHA in the revised Desktop model as initially envisioned will not be possible. This led to the development of the Velocity Depth Guild (VDG) model. This approach is based on the fact that only generic information regarding the width of the stream and the possible proportions of VD classes will be available. The suitability of the habitat must be seen in terms of the width of the stream and suitability can only be calculated in terms of VD categories and width. Other aspects such as cover and life cycles cannot be considered as the information is not available generically.

One of the core components of the model is the use of a desktop approach to defining the characteristics of a representative channel cross-section in the absence of any detailed field surveys. A large part of the development of the parameter estimation process for the hydraulics sub-model was based on a detailed analysis of channel cross-sections and hydraulic data generated by previous Reserve studies (Rapid, Intermediate and Comprehensive). However, these were not sufficient on their own to permit the development of generic and widely applicable parameter estimation equations and it was often necessary to return to some of the basic principles of channel hydraulics and regional relationships reported in the international literature. The final version of the sub-model is based on identifying the appropriate geozone to use, estimating the channel forming flood discharge from regional flood relationships with catchment area and a measure of the valley bottom slope. These are all readily accessible to a potential user, although there will always be some uncertainty in their evaluation depending on the resolution and accuracy of the available information sources.

Chapter 4 represents the first draft of the user manual and explains the structure of the model, how to use it and all of the options that are available to the user for modifying the way in which the Reserve requirements are calculated. The first part of the process involves the analysis of the available hydrology data, which includes observed or simulated time series of natural and present day stream flow data, plus regional parameters to determine how total flows are separated into the low and high flow components. This represents a critical step in the model process as the other parts of the model are mostly based on analyzing the low flows. The main outputs are the critical wet and dry season months and the maximum baseflows that are associated with these months. These are considered to represent the optimum ecological conditions (i.e. zero ecological stress) that are passed on to the hydraulic and ecological sub-models. The hydraulic sub-model generates a representative channel cross-section from the user specified geozone, flood region, catchment area and local valley slope. All of the other parameters of the hydraulic sub-model are fixed. The outputs from the hydraulic sub-model are the stage-discharge rating curve and the proportion of different habitat types (defined by combinations of flow depth and velocity) that are available at all flow rates between zero and the maximum baseflow values.

The ecological sub-model uses the information generated from the hydrology and hydraulics sub-models to define the relationships between flow and ecological stress for the critical wet and dry season months. The flow-stress relationships are based on the changes in habitat availability, using three critical velocity-depth classes (fast-deep, fast-intermediate and fast-shallow), that occur during reductions in flow from the maximum baseflow for the season. These relationships are used together with the flow time series for natural and present day conditions to define stress frequency curves. A set of rules are then used to shift the stress frequency curves away from the natural stress regime for the different ecological Reserve categories (higher stress for lower categories). The user has the option to modify these rules manually (editing the shift values) or to adjust the rules semi-automatically to account for non-perenniality in the dry season or both seasons, or to align one of the categories to the highest stress conditions under the assumed present day situation. The category stress frequency curves are then re-processed using the flow-stress relationships and the natural flow time series to create flow duration curves that can be considered appropriate for the requirements under different ecological categories. Various options are available to plot the results.

The next part of the model provides approximate estimates of the flood requirements for the ecological categories and the approach used is quite similar to the old Desktop Reserve model. This part of the model will require re-investigation in the future and was not the focus of this project. The final part of the model integrates all of the information and estimates to generate assurance curves and time series of flows for all of the ecological categories and summarises the results as annual volumes and percentages of mean annual runoff. At all stages in the model the user has the opportunity to save summaries of the results which are combined into a single report which is saved to the SPATSIM (or SPATSIM HDSF) database and can be printed to a text file.

Chapter 5 reports on some of the assessments of the RDRM that have compared the results of applying the model with outputs from Intermediate or Comprehensive Reserve determinations. The results of the assessments suggest that the model is able to generate sensible low flow Reserve results, despite the limitations of using a desktop approach to generating the hydraulics and an ecological sub-model that also has limitations compared to the much more detailed assessments that form part of normal high confidence Reserve determinations. There is little doubt that after the Beta version of the model has been used for many more sites, modifications to the structure of model will be identified and need to be incorporated. This issue is almost certainly relevant to the approach used to quantify the high flow requirements which were not tested as part of the assessment undertaken in this project. It is also likely to be relevant to some of the low flow quantification methods, but the conclusion at the end of this project is that the model has reached as stage of development where it can be used with acceptable confidence (albeit much lower than a detailed site specific investigation). No detailed comparisons have been made with the estimates provided by the previous Desktop model as this was not considered appropriate. However, the general trend of increasing low flow requirements with decreasing degrees of hydrological variability (a major component of the previous Desktop Reserve model) has been retained within the RDRM, although for different reasons and through a different modelling process.

The overall conclusion is that the RDRM has reached a stage of development (Beta version) where it can be used by practitioners with some caution. The caution is required to ensure that the model does not generate inappropriate results in situations that have yet to be covered by the assessments undertaken by the project team. These are expected to be rare, but if they do occur it may be necessary to make some structural modifications to the model. The project team have already identified several components of the model that could be improved and would add flexibility to the model. Many of the identified improvements are associated with the use of the model to support Rapid, Intermediate or Comprehensive Reserve determinations where additional information is available that the RDRM will need to use. These improvements are therefore not relevant to the use of the model in a totally desktop environment.

With respect to estimating flood requirements, the approach used in detailed Reserve determinations is to identify flood peaks (for up to seven classes) that perform some defined ecological function. The flood peaks are typically related to the channel hydraulics and this provides an opportunity to follow a similar principle within the RDRM. Some of the existing approaches based on the monthly differences between total flow and separated baseflow could be used to identify the months in which flood requirements are expected. A revision to the model would almost certainly require regional information about the typical frequency of events, duration of events of different magnitudes and the conversion factor from instantaneous peaks to mean daily flow peaks (a measure of catchment response time). It should then be possible to use the hydraulics of the model generated channel cross-section to infer an appropriate range of flood peaks.

Part of the original design concept was to include a facility to replace the desktop generated channel cross-section with a surveyed channel cross-section if available. Even with a surveyed channel cross-section it will be necessary to define the shape of the relationships between water depth and the Manning’s roughness coefficient as well as with the water energy gradient.

While a relatively high degree of flexibility in modifying the shapes of the stress frequency curves has already been built in to the model, there is one situation that is not catered for. This situation occurs when the present day flows in one or both seasons are greater than natural flows as a consequence of irrigation releases or return flows. If this situation occurs and is reflected in the difference between the natural and present day flows, it may be appropriate to allow for stress curve shifts that are negative (i.e. decreasing stress as the ecological Reserve category moves from A to D). It is also possible that there should be a reversal of the shift direction between seasons where wet season flows are used to fill reservoir storage (resulting in reduced flow and increased habitat stress), while dry season flows are enhanced with releases from storage (resulting in increased flows and reduced habitat stress). This type of situation can occur below reservoirs operated for hydro-power generation.

The original Desktop model has been applied in several countries outside South Africa and in each case it has been necessary to develop a set of regional parameters that are appropriate to the conditions existing in those other countries. To a certain extent the same will apply for the RDRM. While the parameter estimation routines used for the hydraulics sub-model have been based on approaches used in many countries there is the possibility that some of the equations will not be appropriate. Certainly the flood regions are specific to South Africa and a new set of regions and equations would be needed for other countries. The use of the Geozones are also quite specific to South Africa and are unlikely to be applicable to a wide range of other countries where the channel forming processes may be different. Similarly, the ecological sub-model is based on South African experience, although the use of the Fast Deep, Intermediate and Shallow habitat types should be transferrable to other counties.

The final issue referred to in the report is the need for practical testing and future training. The beta version of the model that has been developed thus far needs to be further tested to evaluate its use in many different situations. The project team recommends that this testing can be achieved as part of the normal roll-out process for the software. It has already been quite thoroughly tested in a number of situations and further testing should concentrate on identifying any situations where it is clearly not appropriate and can be demonstrated to fail in its ability to generate sensible results. Identifying problems therefore needs to be part of the training programme.

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CAPACITY BUILDING

The most direct contribution to capacity building has been through the registration of Mr Ahmed Desai as a PhD candidate at Rhodes University. Mr Desai is employed by IWR Water Resources and registered during 2009 under the joint supervision of Prof Denis Hughes and Dr Andrew Birkhead to undertake research towards the development of the hydraulics sub-model, a very important component of the total revised Desktop Reserve model. Mr Desai has extensive experience of applying ecohydraulic approaches in practical Reserve determinations and was therefore an ideal choice for participation in the project as the hydraulics specialist. Mr Desai is expected to complete the writing of his PhD thesis before the end of 2011 and we have every expectation that he will be awarded the degree during 2012.

Further contributions to capacity building are expected to occur after the project has been completed and the Revised Desktop Reserve Model (RDRM) is applied by staff of the Resource Directed Measures (RDM) Directorate of the Department of Water Affairs (DWA) and their external consultants. The previous Desktop Reserve model has become outdated and is not aligned with the current approaches to setting Reserve requirements. While this model has been used extensively for low-confidence Reserve determinations by DWA staff it does not contribute very much to their understanding of the linkages between hydrology, hydraulics and ecology that are critical to more detailed Reserve determinations (intermediate and comprehensive). The RDRM has the potential to address this issue as it includes the same concepts (albeit at a desktop and therefore low-confidence level) that are used in many major Reserve determination projects. The model should therefore foster an improved understanding of the links that occur between the abiotic drivers (hydrology and hydraulics) and the biotic responses (ecology) that are critical to the concept of the Reserve and setting environmental water requirements of rivers.

GLOSSARY OF TERMS

Baseflow:	The low amplitude, high frequency component of a stream flow time series distinguished from the high flow (high amplitude, low frequency) signal associated with rapid catchment response to individual rainfall events using a mathematical separation method (Hughes et al., 2003).
BF Alpha:	Alpha parameter in the monthly time series baseflow separation method of Hughes et al. (2003).
BF Beta:	Beta parameter in the monthly time series baseflow separation method of Hughes et al. (2003).
BBM:	Building Block Methodology used to set ecological flow requirements in the past and incorporated as part of the original Desktop Reserve model (King and Louw, 1998).
Drought Flows:	One of the 'Building Blocks' of the BBM describing the flows that are required under drought conditions.
Ecological Reserve:	The quantity and quality of water required to maintain the resource in a defined and sustainable ecological state.
Ephemeral:	Description of river hydrological regimes that do not have continuous flow but experience individual flow events strongly linked to rainfall events with no baseflows between events.
EWR:	Environmental or ecological water requirements (the international accepted terminology for the ecological Reserve). EFR or environmental flow requirements is also used.
FD:	Fast, deep habitat type (velocity>0.3 m s^{-1} and 0.3 m≤depth)
FI:	Fast, intermediate habitat type (velocity >0.3 m s^{-1} and 0.2 m≤depth <0.3 m)
Flood Region:	An index value between 1 and 13 representing the flood response region (see Table 4.1 of this report) according to Mkhandi and Kachroo (1997) and used to estimate the maximum channel width in the hydraulics sub-model.
FS:	Fast, shallow habitat type (velocity >0.3 m s^{-1} and 0.1 m≤depth <0.2 m)
FSR:	Flow-Stressor Response method for quantifying Reserves based on relationships between flow and indices of ecological stress (Okeeffe et al., 2002; Hughes and Louw, 2010). The name has changed to HFSR
FVS:	Fast, very shallow habitat type (velocity >0.3 m s^{-1} and depth <0.1 m)
Geozone:	A geomorphological zonal classification system for southern African Rivers providing a geomorphological definition in terms of distinctive channel morphological units and reach types based on channel gradient. (Rountree and Wadeson, 1999)

HFSR:	Habitat Flow Stressor Response method: DWA requested a name change for the FSR so as to explicitly make the link to habitat.
Hydraulic Habitat:	Habitat types based on depth and velocity categories (SVS, SS, SD, FVS, FS, FI, FD).
IFR:	Instream Flow Requirements, old terminology for EWR and the ecological Reserve.
Limnophlic:	These species prefer to live, feed and reproduce in slow-flowing to stagnant water (body shape generally not suited for flowing water, i.e. tilapias). These species can complete all life stages in lotic or slow habitats and do not require fast habitats for any life stage (such as during spawning)
Maintenance Flows:	One of the ‘Building Blocks’ of the BBM describing the flows that are required on a regular basis (but without a full definition of the frequency in the original BBM).
Perennial:	Description of river hydrological regimes that have continuous flow (although in the RDRM this has been interpreted as continuous flow in the wet and dry season).
PES:	Present Ecological State: Describes in terms of an Ecological Category (A-F) the degree in which the present state has changed from natural conditions.
REC:	Recommended Ecological Category: Describes in terms of an Ecological Category (A-F), the desired state of the resource from an ecological perspective.
Rheophylic:	Fish species where all freshwater life stages are confined to lotic waters. They require flowing water during **all phases** of the life-cycle. These species prefer strong flow and clear water, using this habitat both for breeding and feeding.
SD:	Slow, deep habitat type (velocity$\leq$0.3 m s^{-1} and depth >0.5 m).
Seasonal:	Description of river hydrological regimes that generally have continuous flow in the wet season and intermittent or no flow during most dry seasons (a special case of an ephemeral river).
SS:	Slow, shallow habitat type (velocity$\leq$0.3 m s^{-1} and 0.1 m <depth <0.5 m).
SVS:	Slow, very shallow habitat type (velocity$\leq$0.3 m s^{-1} and depth <0.1 m)

.

1 INTRODUCTION

The Desktop Reserve model (Hughes & Hannart, 2003) was developed to enable quick estimates to be made of the ecological Reserve for rivers at any site within the country. The Reserve estimates are currently based on a three stage process and are strongly associated with the concepts of the Building Block Methodology. The first stage is to determine the annual volumes of the low flow maintenance and drought requirements, as well as the maintenance high flow requirements as percentages of the mean annual runoff. ‘Maintenance’ and ‘Drought’ were concepts associated with the Building Block methodology and were early attempts to ensure that some variability (Hughes, 1999) was built into the definition of environmental water requirements (EWR). Within the Desktop model, the determination of the annual requirements is based on empirical relationships with a measure of hydrological variability that is calculated from a reference flow time series. These empirical relationships were developed from an analysis of the results of a number of EWR studies undertaken during the period 1996 to 2002. The relationships are therefore based purely on hydrology and incorporate any inconsistencies in the results that were an inevitable consequence of the developing methods of Reserve determinations during that period.

The second stage is to translate the annual requirements into seasonal distributions. This is based on the seasonal distributions of the reference hydrology time series. The third stage is to combine the monthly maintenance and drought flow Reserve estimates into complete tables (or curves) of assurance rules (equivalent to flow duration curves). The shapes of the assurance rule curves are determined in the model from the values of the maintenance and drought flow estimates as well as the flow duration curve characteristics of the reference flows. It is clear, therefore, that the existing Desktop Reserve model is very dependent upon the characteristics of the reference hydrology used and that it largely ignores the advances in understanding of habitat-flow-ecology relationships that have emerged in the last 5 years or so (Hughes and Louw, 2010). It also ignores regional differences in these relationships that are related to regional differences in the natural biotic assemblages and ecological functioning, as well as differences in the relationships between flow, hydraulics and habitat. The latter are assumed to vary across different geomorphological zones (geozones).

This project was therefore designed to develop hydraulic and ecology (mainly fish and invertebrate) sub-models that can define the seasonal habitat requirements of the dominant species in a region for a range of levels of protection. The ecology sub-model is designed to be linked to the hydrology time series through the hydraulic sub-model. The development of these sub-models has been guided by recent developments in the science and practice of Reserve determinations and represents one of the main inputs into the project as a whole. However, one of the biggest problems that had to be overcome during the project was to decide how these developments could be incorporated into a model that is designed to operate in a Desktop environment without the support of field work and the expertise of experienced individuals. This has proved to be one of the major challenges faced by the project and illustrates the extent to which many Reserve determinations rely upon the expertise and experience of a limited number of individuals. This experience has made many contributions to the evolution of methods that are applied in complex Reserve determination studies (i.e. intermediate and comprehensive type determinations), but in many cases has yet to be fully documented and formalized. As in many other water resources assessments (such as hydrological modelling), experience plays a major role in the successful implementation of some techniques and the practical application of science is something of an 'art'. The objective of developing the RDRM was to draw this experience (and any associated databases) together so that it could be formalized and therefore made accessible to a wider audience of practitioners. The ultimate objective was not to develop a model that would replace that experience, which would be impossible, but to develop a model that would draw on that experience and contribute to improved confidence in the results of rapid desktop assessments undertaken by less experienced individuals.

This report includes some discussion of the concepts of linking hydrology, hydraulics and ecology that have emerged during many years of experience of trying to find sound scientific approaches to setting environmental water requirements (the ecological Reserve) in the rivers of South Africa (Section 2). The part of the report that deals with the hydraulic sub-model (Section 3) provides quite a lot of detail of how that sub-model was developed, tested and refined. This detail has been extracted from the PhD thesis that is being written by Mr Desai and is included as it is the critical link between the hydrology data and the ecological response.

Section 4 provides a quite detailed description of the final model and the links between the different sub-models. This section is mostly focused on explanations of the use of the model (using many screen shots of the software), but also includes some details of the algorithms used (particularly in the ecology sub-model). This section can be used as a preliminary 'User Manual' for application of the model. Some of the algorithms are included to encourage users of the model to develop an understanding of what the model is doing and how the results generated by the model are achieved. While it is recognised that not all users will take the time to develop this understanding, those that do will be better able to assess the results and make informed suggestions for later improvements to the model.

Section 5 discusses the evaluations of the model results against previous intermediate or comprehensive Reserve determinations, while the details of any modifications that were made to the model (or default model parameters) as a consequence of the assessments have already been incorporated into the other sections. Section 6 discusses the way forward in terms of the requirements for future modifications that have already been identified, further testing and the implementation of the model by a wide range of practitioners.

2 LINKING HYDROLOGY, HYDRAULICS AND ECOLOGY

2.1 BACKGROUND

Various studies led and contributed to this current Water Research Commission (WRC) study, K5/1856: DEVELOPMENT OF A REVISED DESKTOP RESERVE ESTIMATION MODEL. In essence, the purpose of this WRC study is to revise the Desktop Reserve Model (DRM) (Hughes & Hannart, 2003).

The studies that contributed to the revision of the Desktop study were initiated to provide Reserve estimates to various nodes in the catchment. The requirement was for an estimate with a higher confidence than the current Desktop Reserve Model by more explicitly including ecological requirements. As the Revised Desktop Ecological Reserve model will only be available in 2011, an interim process to estimate Reserves to various nodes had to be provided.

The background to all the preceding studies is provided below.

2.1.1 2007 WRC and DWA Komati study

The following is an extract of Kleynhans *et al* 2008. In: Principles of a process to estimate and/or extrapolate environmental flow requirements. Report produced for the Water Research Commission, South Africa by Water for Africa (Pty) Ltd. KV 210/08

The Department of Water Affairs and Forestry (DWAF) has announced its Water Allocation Reform (WAR) programme as an important component of the roll out of the National Water Act of 1998. The main focus of the WAR programme is to reconcile existing and future water demands with its availability. Water resource planning requires recognition of the Ecological Reserve, and estimates of Ecological Water Requirements (EWRs) are therefore required.

Ecological Reserve (quantity) determinations at the Comprehensive and Intermediate levels have generally been determined for sites located along main-stem rivers and major tributaries, where water resources are often in high demand. Frequently, no EWR information is available for the smaller tributaries. The establishment of sites to provide EWRs at all locations of interest necessary for water resource planning is not pragmatic and beyond available resources. There is therefore a need to develop a cost-effective and efficient method for estimating EWRs for numerous river locations with reasonable levels of accuracy. This requirement is necessary to support the WAR initiative and to better evaluate individual water use licence applications.

The primary objective of this project was to develop a procedure for extrapolating EWR low-flow result from Reserve sites to additional locations (termed hydro-nodes) that have a degree of ecologically similarity. The extrapolation procedure refers to hydrological extrapolation by adjusting default parameters in the Desktop Reserve model, and is the *current approach for estimating EWRs for additional river locations. The Desktop Reserve model is based on the results of previous EWR assessments, and therefore almost entirely on EWR-hydrological relationships derived for rivers with substantial runoff. With the exception of Rapid level III estimates, little cognisance is given as to whether hydrological extrapolation is ecologically justified. The "extrapolation" concept was extended to the "estimation" concept at an early stage of the study. The reason for this is that an "estimation" approach does not limit the method to the use of existing Ecological Reserve results, but rather allows for the development of a method that explicitly incorporates biological information, flow preferences for the biota present, and availability of hydraulic habitat.*

A procedure has been developed for establishing the extent to which different river locations have physical similarity. Based on this, the assumption is that physical similarity implies similar fish guilds under natural conditions. The identification of likely indicator species may subsequently be used for informing ecological flow requirements at additional (un-sampled) river locations.

Estimation of EWRs requires the definition of habitat preferences or requirements. These have been provided through habitat specifications (or HabSpecs), which are numerical values for a combination of hydraulic parameters and flow-classes that define required hydraulic habitat and hence flows for "groups" of biota that exploit environmental resources in a similar way (referred to as guilds for fish and communities for invertebrates). Habitat specifications are a function of hydrological variability (e.g. drought, maintenance and season) and Ecological Category (EC) for the river. In this study, HabSpecs were determined for two fish guilds: small rheophilic fish and large semi-rheophilic fish and a single community of invertebrates – cobble-dwelling rheophilics. Habitat specifications were computed using an optimisation method based primarily on the results of previous EWR studies. This effectively provides "calibrated" numerical rules that are based on the collective knowledge and understanding of river ecologists involved in previous ecological flow assessments. Habitat specifications provide a simple and consistent rule-based approach for estimating EWRs where hydraulic characterisation of flow conditions is available – presently at Rapid level III assessments and higher.

The HabSpecs indicate that hydraulic habitat is more sensitive to changes in low flows in smaller rivers (MAR < –30 Mm^3/a) than larger rivers, with the relevant fish guilds and invertebrate communities used, which supported by studies in the international literature.

The Nkomati Water Availability Assessment Study (WAAS) formed the basis for application of the methods (site similarity and EWR estimation) developed within this study. Overall, the HabSpec predicted ecological flows for 10 tributary sites were considered to provide more reasonable estimates, compared with Desktop model generated values, for the smaller streams with lower MARs (below – 30 Mm^3/a) and small rheophilic fish. Desktop model estimates were considered to provide increasing underestimates of EWRs with reducing stream size below approximately 30 Mm^3/a. For sites with mean annual runoff in excess of approximately 30 Mm^3/a, Desktop model estimates were considered reasonable recommendations for ecological low-flows. Since the HabSpec estimation method is *independent of hydrology, estimates should be confined to between Desktop and natural (albeit modelled) flows. For the sensitive rheophilic biota considered, the application of HabSpecs for EWR estimation indicates that higher proportions of natural flows are required with reducing stream size and during the drier season.*

The HabSpec generated low-flows for the selected (tributary) river sites were expressed as a function of the inundated low-flow channel width, and unit-width discharges were found to be remarkably constant. These flows were used to define the minimum seasonal drought and maintenance discharges required to achieve the recommended EC for the sensitive rheophilic biota. It needs to be emphasized that the unit-width EWR results from this study are applicable to specific fish guilds and invertebrate communities and hydrological characteristics of the Nkomati River catchment. Further study is required for the reasoning behind this (unit width) finding, as well as the development of more generalised and tested procedures for estimating EWRs for different biota and geomorphologies. This is taking place during concurrent research projects funded by the Water Research Commission as well as DWAF Reserve studies.

2.1.2 K8/795: Collation and synthesis of hydraulic information from Environmental Flow Requirement studies

The above analysis was undertaken by Birkhead and Desai. The following is an extract of the draft WRC report.

Large quantities of river hydraulic information have been collected over the past decade in the course of undertaking Environmental Flow Requirement (EFR) assessments (including Instream Flow Requirements), and more recently, Ecological Reserve studies. The clients involved have been mainly the Department of Water Affairs (South Africa), as well as private organisations and government departments in neighboring countries (e.g. Swaziland, Lesotho and Mozambique). These data are in electronic format and hardcopies in the form of project reports, electronic files (workbook data), and total approximately 46 projects, 218 sites and 821 cross-sections.

Kleynhans et al. (2008) discuss the principles of a process to estimate and/or extrapolate Environmental Flow Requirements. The estimation component requires the prediction, at the desktop level, of the (ecologically relevant) low-flow inundated channel width. The (current) Water Research Commission (WRC) project (K5/1856), requires the development of a hydraulics sub-model for estimating hydraulic habitat. This information will be used for the WRC project but was also extensively used in the determinations of the approaches used in the interim to estimate Ecological Reserves at various nodes.

The objectives of this project have been to:

- *Collate available hydraulic and relevant site-related information from previous (mainly) EFR studies, and*
- *determine whether the data display empirical relationships.*

2.1.3 Crocodile (east), Sabie-Sand, Mokolo and Upper Vaal Comprehensive Reserve studies

The above studies all included a task which was to estimate and/or extrapolate EWRs to various hydronodes, i.e. similar to the Komati process described in 1.1. As this work was to be finalised prior to the concurrent WRC study being finalised, the per unit width approach was used with some modifications. These results are produced in:

Inkomati Reserve study:
Department of Water Affairs, South Africa. 2010. Comprehensive Reserve Determination Study for Selected Water Resources (Rivers, Groundwater and Wetlands) in the Inkomati Water Management Area, Mpumalanga. Sabie-Sand and Crocodile Systems: Estimation and extrapolation of EWRs at selected hydronodes. . Prepared by Rivers for Africa, Authored by Louw, MD and Birkhead, AL. RDM Report no 26/8/3/10/12/007.

Mokolo Reserve study:
Department of Water Affairs (DWAF), 2010. Intermediate Reserve determination study for Selected Water Resources (Rivers and Groundwater) in the Mokolo Catchment. Estimation and extrapolation of EWRs at selected hydronodes. . Prepared by Rivers for Africa, Authored by Louw, MD and Birkhead, AL. Report no: 26/8/3/10/14/007

Although this work still focussed on the per unit width approach, all the data collated for the database of available information contributes directly to the current WRC study. This data relates to:

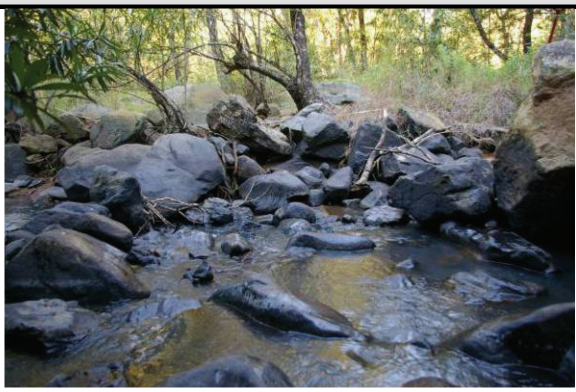
- Calibration and EWR sites (Table 1.1 – Table 1.4) surveyed and hydraulics provided
- Fish and invertebrate requirements for B, C and D Ecological Categories provided for each of the sites
- Hydronodes characterised and indicator species predicted.

Table 2.1 Calibration sites in the Sabie and Crocodile River systems used for EWR estimation (Photographs: D. Louw)

SABIE AND CROCODILE RIVER SYSTEMS: CALIBRATION SITES FOR ESTIMATION	
	
Sekgamarago	**Buffelskloofspruit (cross-section A)**

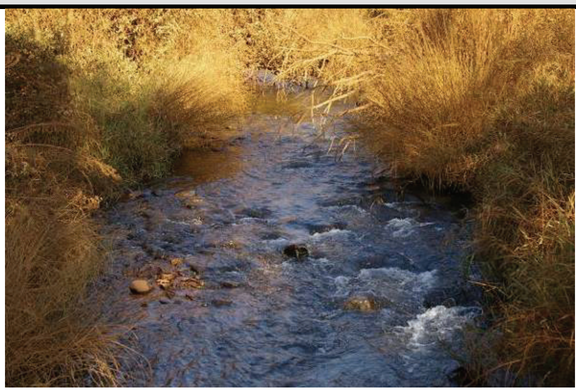
Buffelskloofspruit (cross-section B)

Lonely Creek



Sabane

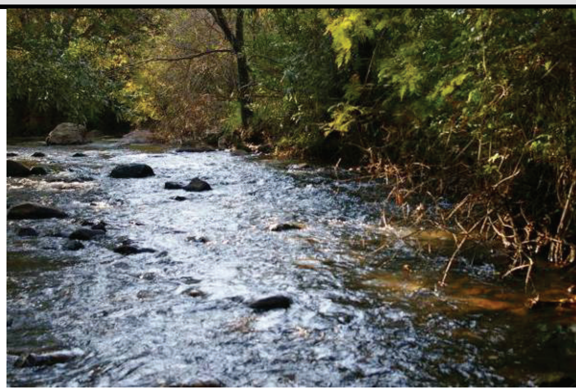
Blyfstaanspruit



Sabie

Nels

Noord Kaap



Houtbosloop

Table 2.2 **Calibration sites in the Mokolo River system used for EWR estimation (Photographs: D. Louw)**

MOKOLO SYSTEM RIVER SYSTEM: CALIBRATION SITES FOR ESTIMATION	
	
Rhenosterpoortspruit (cross-section A)	**Rhenosterpoortspruit (cross-section B)**
	
Sand	**Klein-Vaalwaterspruit**
	
Jim se Loop	**Tambotie (cross-section A)**
	
Tambotie (cross-section B)	**Frikkie se Loop,**

	
Upper Dwars	**Lower Dwars (Cross-section B)**
	
Sterk	**Taaibos**

Table 2.3 Calibration sites in the Upper Vaal River system used for EWR estimation (Photographs: D. Louw)

UPPER VAAL RIVER SYSTEM: CALIBRATION SITES FOR EWR ESTIMATION	
	
Klip	**Grootspruit (cross-section B)**
	
Cornelius	**Skulpspruit**
	
Kromelmboogspruit	**Kromspruit**
	
Meul (cross-section A)	**Meul (cross-section B)**

	
Holspruit	**Waterval**

Table 2.4 Sites used for hydronode EWR estimation

Quat	Site nr	River	Alt (m)	Co-ordinates		MAR (Mm^3)	Discharge (m^3/s)[1]	Ind fish guild[2]		Ind invert taxa[3]		% pt FDT[4]	
				Latitude	Longitude			Dry	Wet	Dry	Wet	Maint[5]	Dry
NKOMATI RIVER CATCHMENT													
Calibration sites													
X12K	X12K1	Phalangampepe	731	-26.0453	31.0503	4.2	0.050	SR	SR	FDCD[6]	FDCD	70	95
X12G	X12G2	Bergstroom	1200	-25.9678	30.8333	4.8	0.026	SR	SR	FDCD	FDCD	70	95
X11F	X11F1	Bankspruit	1545	-25.8469	30.3506	6.7	0.075	SR	SR	FDCD	FDCD	70	95
X12G	X12G1	Mawelawala	1144	-25.9652	30.8216	9.9	0.037	SR	SR	FDCD	FDCD	70	95
X12H	X12H2	Sandspruit	800	-26.0497	30.8972	10.5	0.037	SR	SR	FDCD	FDCD	70	95
X11A	X11A1	Vaalrivierspruit	1531	-26.0069	30.02664	10.6	0.019	SR	SR	FDCD	FDCD	70	95
X11D	X11D1	Klein Komati	1640	-25.8881	30.1203	10.7	0.050	SR	SR	FDCD	FDCD	70	95
X12K	X12K2	Mlondozi	1098	-26.0472	31.0442	14.2	0.17	SR	SR	FDCD	FDCD	70	95
X11E	X11E1	Swartspruit	1444	-25.93695	30.235	15.4	0.045	SR	SR	FDCD	FDCD	70	95
X12B	X12B1	Buffelspruit	1562	-26.0628	30.3939	27.9	0.086	SR	SR	FDCD	FDCD	70	95
X11G	X11G3	Komati	935	-25.9531	30.7249	370	1.5	LSR	LSR	FDCD	FDCD	70	95
SABIE and CROCODILE RIVER CATCHMENTS													
Calibration sites													
X32A	E8Sek	Sekgamarago	886	-24.69327	30.92953	1.0	0.02	SR	SR	FDCD	FDCD	70	95
X21D	E2aBKS	Buffelskloofspruit	1184	-25.43842	30.44713	10.8	0.10	SR	SR	FDCD	FDCD	70	95
X21D	E2bBKS	Buffelskloofspruit				10.8	0.10	SR	SR	FDCD	FDCD	70	95
X31G	E9Lon	Lonely Creek	1146	-25.10324	30.71097	11.2	0.34	SR	SR	FDCD	FDCD	70	95
X31D	E6Saban (a)	Sabane	533	-25.03414	31.01989	16.4	0.031	SSR	SSR	FDCD	FDCD	70	95
X31D	EcSaban (b)	Sabane						SSR	SSR	FDCD	FDCD	70	95
X22A	E3Bly	Blyfstaanspruit	1032	-25.28752	30.59633	19.3	0.51	SR	SR	FDCD	FDCD	70	95
X31A	E10Sab	Sabie	1099	-25.12100	30.71700	26.5	0.41	SR	SR	FDCD	FDCD	70	95
X22D	E5Nels	Nels	1065	-25.28945	30.76464	30.4	1.2	SR	SR	FDCD	FDCD	70	95
X32B	E1Kaap	Kaap(North)	678	-25.60761	30.97650	43.5	0.27	SR	SR	FDCD	FDCD	70	95
X22A	E4Hout	Houtbosloop	865	-25.35516	30.66591	56.8	0.78	SR	SR	FDCD	FDCD	70	95
EWR sites													
X31B	EWR 1	Sabie	862	-25 04.424	30 50.924	140.2		SR/LR	SR/LR	FDCD	FDCD	70	95
X31D	EWR 2	Sabie	463	-25 01.675	31 03.099	262.1		SR/ R	SR/LR	FDCD	FDCD	70	95
X31K	EWR 3	Sabie	369	-24 59.256	31 17.572	495.9		SR/SR	SR/SR	FDCD	FDCD	70	95
X31C	EWR 4	Mac Mac	582	-25 00.800	31 00.243	65.8		SR/ R	SR/LR	FDCD	FDCD	70	95

Quat	Site nr	River	Alt (m)	Co-ordinates		MAR (Mm³)	Discharge (m³/s)[1]	Ind fish guild[2]		Ind invert taxa[3]		% pt FDT[4]	
				Latitude	Longitude			Dry	Wet	Dry	Wet	Maint[5]	Dry
X31G	EWR 5	Marite	457	-25 01.077	31 07.997	157.1		SR/ R	SR/LR	FDCD	FDCD	70	95
X32C	EWR 7	Tlulandziteka	543	-24 40.829	31 05.188	28.9		SR/LSR	SR/LSR	FDCD	FDCD	40	95
X21A	EWR 1	Crocodile	1852	-25 29.647	30 08.656	15.2				FDCD	FDCD	70	95
X21B	EWR 2	Crocodile	1207	-25 24.555	30 18.955	47.1		SR	SR	FDCD	FDCD	70	95
X24H	EWR 6	Crocodile	470	-25 38.968	31 14.572	1063		SR/LSR	SR/LSR		FDCD	70	95
MOKOLO RIVER CATCHMENT													
Calibration sites													
A42F	8	Taaibos	1011	-24 11.128	27 51.673	1.8	0.49	SSR	MSR	FDCD	FDCD	50	95
A42B	2XSA	Rhenosterpoort-spruit	1284	-24.50804	27.86574	1.9	0.081	SSR	MSR	FDCD	FDCD	50	95
A42B	2XSB	Rhenosterpoort-spruit						SR	SR	FDCD	FDCD	50	95
A42A	1	Sand	1356	-24.65283	28.231	2.1	0.14	SR	SR	FDCD	FDCD	50	95
A42E	11	Klein Vaalwaterspruit	1098	-24.21941	28.05363	2.7	0.42	SSR	LSR	FDCD	FDCD	50	95
A42E	6	Jim se Loop	1209	-24.27184	28.20002	2.8	0.19	SSR	MSR	FDCD	FDCD	50	95
A42H	7XSB	Tambotie	983	-23.81291	27.94885	2.8	0.52	MSR	MSR	FDCD	FDCD	50	95
A24D	9	Frikkie se Loop	1221	-24.31397	27.95724	3.9	0.66	SR	SR	FDCD	FDCD	50	95
A42E	4	Upper Dwars	1188	-24.26661	28.21718	10.3	0.46	SSR	LSR	FDCD	FDCD	50	95
A42E	5XSA	Lower Dwars	1212	-24.26736	28.21873	14.1	0.66	SSR	LSR	FDCD	FDCD	50	95
A42E	5XSB	Lower Dwars						SSR	LSR	FDCD	FDCD	50	95
A24D	10	Sterk	1191	-24.30554	27.89699	26.1	2.2	SR	SR	FDCD	FDCD	50	95
UPPER VAAL RIVER CATCHMENT													
C13C	8 (UVKlip)	Klip	1757	-27.82105	29.64983	5.75	0.14	SSR	SSR	FDCD	FDCD	60	95
C82F	3B(UV36)	Grootspruit	1643	-27.49946	28.95117	6.24		LSR	LSR	FDCD	FDCD	60	95
C82A	7(UVCor)	Cornelius	1852	-27.83821	29.35921	7.93	0.006	LSR	LSR	FDCD	FDCD	60	95
C11E	9(UV9)	Skulpspruit	1635	-27.02988	29.88956	12.11	0.004	LSR	LSR	FDCD	FDCD	60	95
C23B	1(UV53)	Kromelmboog-spruit	1416	-26.79594	27.56550	14.36	0.006	LSR	LSR	FDCD	FDCD	60	95
C83K	2(UV45)	Kromspruit	1492	-27.25842	28.40691	25.72	0.006	LSR	LSR	FDCD	FDCD	60	95
C81L	6B(UV25)	Meul	1691	-27.97461	29.31991	26.50	0.35	LSR	LSR	FDCD	FDCD	60	95
C82G	5(UV31)	Holspruit	1558	-27.67999	28.79244	32.93	0.049	SR	LSR	FDCD	FDCD	60	95
C81M	6A(UV28)	Meul	1588	-27.96968	28.89911	103.85	0.94	LSR	LSR	FDCD	FDCD	60	95
C12G	4(UVWV)	Waterval	1499	-26.96028	28.74577	176.80	0.48	LR	LR	FDCD	FDCD	60	95

1 Single measured discharge for Rapid III level assessment
2 Indicator fish guild
3 Indicator invertebrate guild
4 Percentage point (time equalled or exceeded) on the flow duration table
5 Maintenance
6 Flow Dependant Cobble Dwelling invertebrates

2.2 CURRENT WRC STUDY

The Desktop Reserve model (Hughes & Hannart, 2003) was developed to enable quick estimates to be made of the Ecological Reserve for rivers at any site within the country. The Reserve estimates are currently based on a three stage process and are strongly associated with the concepts of the Building Block Methodology. The first stage is to determine the

Annual volumes of the low flow maintenance and drought requirements, as well as the maintenance high flow requirements as percentages of the mean annual runoff.

The second stage is to translate the annual requirements into seasonal distributions. This is based on the seasonal distributions of the reference hydrology time series. The third stage is to combine the monthly maintenance and drought flow Reserve estimates into complete tables (or curves) of assurance rules (equivalent to flow duration curves). The shapes of the assurance rule curves are determined in the model from the values of the maintenance and drought flow estimates as well as the flow duration curve characteristics of the reference flows.

It is clear, therefore, that the existing Desktop Reserve model is very dependent upon the characteristics of the reference hydrology used and that it largely ignores the advances in understanding of habitat-flow-ecology relationships that have emerged in the last 5 years or so. It also ignores regional differences in these relationships that are related to regional differences in the natural biotic assemblages and ecological functioning, as well as differences in the relationships between flow, hydraulics and habitat. The latter are assumed to vary across different geozones.

The pressures on DWAF to generate Reserve estimates are well known and partly related to the Water Allocation Reform (WAR) program and the need to give effect to the National Water Act. The Desktop Reserve model has been demonstrated to be an appropriate analysis tool, whether used with default parameters or after adjustment through a Rapid Reserve assessment. However, the uncertainty associated with the outputs from the Desktop Reserve model remains a major concern, especially if these outputs are ever likely to be challenged in a court of law.

Improvements to the desktop model require the incorporation of more of our understanding of the ecological processes into the model so that it is not only driven by hydrology.

The ecological component of the WRC study follows directly on from the existing project (K8/657) where the major focus has been to establish the principles and concepts of ecological similarity of sites and using filter models to identify the indicator species at approximately 800 fish sites in the country. The broad principles to specify habitat requirements (linked to the indicator species/groups, geozones and river width/size) were determined and tested on the cobble bed systems in the Komati River.

The HabSpecs component of the study will make use of our understanding of the habitat requirements of the fish and invertebrate indicator species and develop a rule base for habitat requirements under different Reserve categories (i.e. different levels of ecological protection). The outputs from this task will be used as the ecological inputs into the hydraulic sub-model.

2.3 PLANNED APPROACH TO ECOLOGICAL SUBMODEL: RESULTS OF FEBRUARY 2010 WORKSHOP

On 22 February 2010, a workshop was held to discuss the ecological sub model. The workshop only took place during 2010 as it was essential to undertake all studies associated with the Ecological Reserve determinations (Section 1.3) first.

The following decisions were made at the workshop:

a) The approach based on the per unit width requirement as used for the current Reserve studies for estimating the EWRs for hydronodes will not be explored further.
b) An independent approach will be followed by ecologist to produce the generic habitat suitability ratings as a function of river size, guild/taxa and hydraulics parameters/flow classes.
c) Dr Birkhead will not be undertaking any analysis to find best fit requirements for the data.

The initial approach that was decided on was to use aspects of the Fish Flow Habitat Assessment (FFHA) method for the ecological input into the revised Desktop Model. The FFHA was adjusted for use for invertebrates. The following actions had to be undertaken:

Habitat suitability ratings

Generic habitat suitability ratings (see example of the habitat suitability rating tables for fish attached as a separate file), must be set up for the different river sizes and different guilds. The different ***river sizes*** are in m:

- 0-2
- 2-5
- 5-10
- 10-25
- 25-50
- 50+

The ***guilds for fish*** will be

- Small Rheophilic
- Large Rheophilic
- Small Semi-rheophilic
- Large Semi-rheophilic
- Small Limnophilic
- Large Limnophilic

Medium is not included

The assumptions made were that only U-shaped channels with riffles, rapids and runs would be dealt with.

The following actions were required

a) The EWR requirements for different ECs: The FFHA translates natural flow into stress of 0, which reflects an A EC. The degree of deviation in terms of habitat from this natural state is then translated into habitat stress which falls into a specific Ecological Category (A to F). The deviation in habitat is measured according to the change in suitability of habitats for fish and invertebrates. The relationship between habitat change and the links to Ecological Category is coded in the FFHA and it was planned to incorporate this coding in the revised Desktop Reserve model.

b) Prediction of indicator fish guilds: Initially the indicator fish guilds will be established for various points, i.e. a point coverage will be used. The FROC points and all the hydronodes where guilds were already predicted for the Reserve studies will be provided to for inclusion in the Desktop Reserve Model. In the long-term, the indicator guild for every quaternary catchment and then for sub-quaternary level should be determined. For this first prototype model, one might only have to use the point coverage with potentially some guidelines on how to extrapolate to other areas.

Dr Kotze was tasked to assist Dr Kleynhans with linking the FROC species assemblage to habitat guilds, with specific reference to different velocity-depth guild requirements. The envisioned approach would be that all the species will be divided into habitat guilds with maximum sizes as provided in the literature. Dr Kleynhans will then provide a lookup table for the guilds per point. Aspects of juveniles of large species that occur in smaller streams must also be included, as well as large species that might periodically use the smaller stream.

2.4 FISH APPROACH: VELOCITY DEPTH GUILD MODEL (CJ KLEYNHANS. RQS:DWA)

Note: The following is a summary of various Emails written by Dr CJ Kleynhans regarding the VDG model.

It was indicated by Dr Kleynhans (pers comm, 2010) that the use of the FFHA in the revised Desktop model as initially envisioned will not be possible. This led to the development of the Velocity Depth Guild (VDG) model for use within the – Desktop model.

2.4.1 Initial development of the VDG approach

The more reasonable VDG approach is summarised below:

- The U-shaped channel is not realistic (too generic) – it would have only one depth and consequently only one VD class. A 'shape-free' channel approach was followed.
- For the ‘shape-free’ approach it was argued that the most realistic direction would be to work with a situation where the stream width is proportioned according to the four velocity-depth (VD) classes (depth and velocity are obviously already build into the definition of a VD class).

The following decisions and steps in the development process are summarised below:

- An arbitrary width of 50 cm was considered as the minimum where useable habitat for a fish spp would be present.
- The width of a VD class can therefore only be 0 or 50 cm (or multiples of 50 cm) in a stream width.
- The stream width decided on as a starting point was 2 m. This means that one can have FS, FD, SS and SD width combinations that varies, e.g. 50, 50, 50, 50 cm or 0, 50, 50, 100 cm. The various combinations of 50 cm VD "width-blocks" then have to be worked out and the suitability of these combinations according to 6 key considerations (e.g. spawning, nursery areas, connectivity of habitats, WQ, etc.) for various habitat guilds be estimated (expert knowledge based). Working out the various 50 cm width block combinations will have to be calculated manually, and then each combination must be assessed for suitability for various habitat guilds assess.
- By implication, the minimum stream width that one would be able to deal with in such an approach would be 50 cm (i.e. only one VD class present)
- If one considers larger streams, the options were to increase the stream width with regular increments of 2 m (i.e. 2, 4, 6, 8 m, etc.) – different combinations of VD width-blocks. This will again have to be considered and each guild rated according to the perceived suitability for that guild.

Another option was to:

- Start from a stream of 50 cm wide (i.e. only one VD class) and increase stream size with increments of 50 cm. This provides the option of dealing with very small/narrow streams and also almost anything else. Again the combinations come into the picture as well as the suitability rating of these combinations for a particular guild.

To limit the number of individual suitability ratings that needs to be done for a guild, the 50 cm width-blocks should be considered. For instance, the more width blocks of a particular VD class there are, the higher the suitability of the stream width for that particular habitat guild; for instance if the stream is 2 m wide, and 50 cm is FS, it would mean that suitability for a small rheophilic is 25%; in larger streams, the more FD blocks there are, the higher the suitability for that guild; e.g. a stream width of 40 m may have 40, 50 cm FS width blocks, and the suitability for a small rheophilic guild will then be 50%.

Some initial issues regarding the VDG model were the following:

- Only 4 guilds (SR, LR, SL and LL; it may be necessary to also include the semi-rheophilic guild) are considered. This means that particular life-history requirements and other parameters are not included specifically as would be the case when one focuses on an indicator spp. Habitat suitability is thus evaluated for all guilds in terms of general suitability. Habitat suitability for breeding requirements is therefore not addressed specifically.
- It is necessary to obtain some indication of the duration of these widths. One of the key issues would be whether the stream is perennial or not because that has a crucial input in the interpretation of the guilds that can potentially be present.

- The hydraulics aspect of the VDG is covered very broadly by the generic VD-class (i.e. the multiples of 0.5 for VD-classes). If one needs less generic results (e.g. more realistic VD classes, depth and proportions), one will have to provide such information based on some regionalization approach that considers the size of the stream, etc.
- An important consideration is the issue around breeding habitat requirements. Basically what it comes down to is whether one should generate two stress curves: one for the wet season, one for the dry season. During the wet season reproduction requires specific habitats that means more flow (or certain VD-class sizes and widths), and this is currently dealt with in the FFHA by using the maximum natural low flow as the no stress specification. However, during the dry season such flows are not required and one can actually set the overall maximum natural low flow lower by using the dry season maximum low flow and the use of 2 stress curves in the same river must be investigated.

2.4.2 VDG prototype for use in the Revised Desktop Reserve Model

During the development and testing of the initial prototypes, the follow adjustments were made:

- FVS, FS, FD, SVS, SS, SD were included in the model. FVS and SVS are not considered directly in calculation regarding habitat suitability. At this stage the data is not available and the assumption is that these VD classes are not suitable habitat for fish.
- The 0.5 m habitat blocks are not required.
- Only Rheophilics and Limnophilics (small and large) should be used. If FD and FS are present, then it is suitable habitats for Rheophilics and Semi-Rheophillics. If there is no fast flow, or zero flow, then it is also suitable habitat for Semi-Rheophillics and Limnophyllics.

The approach is therefore based on the fact that only generic information regarding the width of the stream and the possible proportions of VD classes is available. The suitability must be seen in terms of the width of the stream.

It must be noted that suitability can only be calculated in terms of VD categories and width. Other aspects such as cover and life cycles cannot be considered as the information is not available generically.

Further development will include development of a stress profile for each VD-guild. If information on flow durations and stream widths can be provided by the other sub-models, the fish VD-guild response in terms of habitat stress (VD classes) durations can be calculated and provided according to ecological categories

a) VDG model: example

Populating the Excel model (requires the following)

- The width of the stream is typed into A2, i.e. the column headed: Enter reference width.
- The VD classes for every 0.5 m are then entered in the column: Width (m) of VD class. The total must add up to the width of the stream entered (16 m in the example).
- The proportional division of VD classes are interpreted in terms of suitability of habitat guilds.
- If FD is present it will add to the suitability for SR (and obviously LR as well). The same is relevant for SD that also provides habitat for SSR (and Limnophyllics that has not been included).

ENTER REFERENCE WIDTH (m)	VD CLASS	WIDHT (m) OF VD CLASS	% of stream width	number of .5 m width-blocks per vd class	HABITAT GUILD (BASED VD REQUIREMENT)	STREAM PROPORTIONAL SUITABILITY	COMBINED SUITABILITY FOR SR(FS+FD) AND SSR(SS+SD)	REFERENCE SUITABILITY= 5	STRESS SCALED OUT OF 10 (NO STRESS=0; MAXIMUM STRESS=10)
16	FVS	3.96	25	7.92	NONE	1.24	1.24		
	FS	4.78	30	9.56	SR	1.49	2.58	5.00	0.00
	FD	3.46	22	6.92	LR	1.08	1.08	5.00	0.00
	SVS	1.3	8	2.6	NONE	0.41	0.41		
	SS	1.5	9	3	SL	0.47	0.78	5.00	0.00
	SD	1	6	2	LL	0.31	0.31	5.00	0.00
	TOTAL	16	100	32					4.00
									0.00

	HABITAT SUITABILITY			
WIDTH	SR	LR	SSR	LSR
16.00	5.00	5.00	5.00	5.00
12.00	3.12	2.03	5.00	2.50
8.00	1.12	0.00	5.00	1.25
6.00	0.39	0.00	5.00	1.00
4.00	0.02	0.00	0.96	0.20
1.00	0.00	0.00	0.00	0.00

	GUILD STRESS ESTIMATED				
INT STRESS	SR	LR	SSR	LSR	WIDTH
0.00	0.00	0.00	0.0	0.0	16.00
3.67	3.75	5.94	0.0	5.0	12.00
6.31	7.76	10.00	0.0	7.5	8.00
6.80	9.21	10.00	0.0	8.0	6.00
9.41	9.95	10.00	8.1	9.6	4.00
10.00	10.00	10.00	10.0	10.0	1.00

Figure 2.1 Illustration of the VD guild model Excel spreadsheet

b) Ecological Categories and the FFHA

The explanation of how the FFHA is used to determine EWR for different Ecological Categories is summarised below:

- The reference (natural) hydrology (Flow duration table) is used to specify the reference habitat conditions that would result from this hydrology. This is done by assessing the habitat conditions in terms of VD-classes (at different discharges) as provided by the hydraulics. Essentially, the hydraulics is converted into VD classes for a range of discharges (plus the other parameters relevant to the habitat).
- A range of flows (zero flow plus 10 other flows; with stress=10 to stress=0; Stress =0 is specified as the maximum natural low flow) is selected and tested to assess the response of the VD-classes (%, width, etc.).
- A suitable species (or guild) is selected as the indicator of stress-response to the habitat response to different flows. For each flow selected, the habitat suitability for various attributes of the population (connectivity, cover, abundance, physico-chemical attributes (mainly flow related, e.g. oxygen and temperature), etc.) as well as certain life-history requirements (e.g. spawning – but not the flood component; and nursery habitat) are rated according to a scale of 0 to 5, with 5 being the maximum. This means that at the maximum natural low flow, all the ratings would be 5 and this would indicate (per definition) that this is the optimum for the site under natural conditions. This would relate to a stress= 0.
- The suitability of the habitat at all other flows < reference are rated based on expert knowledge and available information on the requirements of the spp/guild. The ratings of habitat suitability for the spp are combined and expressed as a (stress) score out of 10 for each flow. This provides the stress table that are converted to an integer scale of 0-10. The result is the flow at each stress, as well as the unsuitability/suitability of the habitat for the various spp/guild requirements (i.e. stress) at each flow (all this follows a simple linear interpolation process).
- The reference flows for each of the VD table percentiles (17 percentiles) are then used to calculate the resulting habitat suitability (stress) for the spp/guild and also for each of the species/guild suitability parameters. Each of these flows-stresses is defined as category "A" or 100%. This means that even under natural conditions there will be stress when flows drop naturally. It is only at the maximum natural low flow that stress would be "0" (i.e. per definition for that particular, river- >reach- >site; it has to be assumed that the site and cross section is representative of the reach characteristics).
- The process above is done for the selected wet and dry months.
- Categories B-F: The approach followed is to derive the B-F ecological categories by simply expressing the stress as derived from the reference (A) for each percentile as a proportion of the natural and with reference to the Table (such a table can be much more specific if EcoSpecs and Thresholds of Concern for a site is specified) below:

Percentage:
100-92=A
92-88=A/B
88-82 = B
82-78 = B/C
78-62=C
62-58=C/D
58-42=D
42-38=D/E
38-22=E
22-18=E/F
<8=F

- The original basis of the Ecological Categories and associated percentages is provided in the table below:

Table 2.5 Original basis of Ecological categories

Class rating	Description of generally expected conditions for integrity classes	Relative FAII score (% of expected)
A	Unmodified, or approximate natural conditions closely.	90 to 100
B	Largely natural with few modifications. A change in community characteristics may have taken place but species richness and presence of intolerant species indicate little modification.	80 to 89
C	Moderately modified. A lower than expected species richness and presence of most intolerant species. Some impairment of health may be evident at the lower limit of this class.	60 to 79
D	Largely modified. A clearly lower than expected species richness and absence or much lowered presence of intolerant and moderately intolerant species. Impairment of health may become more evident at the lower limit of this class.	40 to 59
E	Seriously modified. A strikingly lower than expected species richness and general absence of intolerant and moderately intolerant species. Impairment of health may become very evident.	20 to 39
F	Critically modified. An extremely lowered species richness and an absence of intolerant and moderately intolerant species. Only tolerant species may be present with a complete loss of species at the lower limit of the class. Impairment of health generally very evident.	0 to 19

- This is done for each of the percentiles and for the FFHA a simple calculation-proportioning that does this for the dry season and wet season based on the natural hydrology for these seasons has been developed. This is an approximation and one needs to do a check-up of the habitat response to make sure that the spp requirements and the habitat available at a flow and percentile really provide habitat and stress that is in ‘synch’ with the category that the automatic proportioning provide. Obviously the interpolation process is an approximation with inherent (and unspecified) errors.
- The stress at different percentiles is weighted according to the ‘argument’ that a flow at the 50%tile would have a weight of 1, with decreasing weights for the increasing and decreasing percentiles both sides of the median (for the wet (and dry) season, this weighting processes stops at the %tile where the maximum natural low flow is specified).

- The category for a season is again based on a comparison with the natural (i.e. the proportions (of the natural) of all percentiles are added up and expressed as a % of the natural with the corresponding category. The wet and dry season are similarly combined to provide an overall category. Again: one needs to check that the results are ecologically and biologically meaningful.

FLOW DURATION	WEIGHT
0.10%	0.0020
1.00%	0.0200
5.00%	0.1000
10.00%	0.2000
15.00%	0.3000
20.00%	0.4000
30.00%	0.6000
40.00%	0.8000
50.00%	1.0000
60.00%	0.8000
70.00%	0.6000
80.00%	0.4000
85.00%	0.3000
90.00%	0.2000
95.00%	0.1000
99.00%	0.0200
99.90%	0.0020

- If a 'new' flow scenario (provided as 17 percentiles) is proposed, the option where these flows are entered and the FFHA calculate the category based on the natural hydrology is included.

2.5 FISH GUILD INFORMATION (DR P KOTZE, CLEANSTREAM)

2.5.1 Introduction

The background to the necessity of this study is provided in Chapter 3. The main aim of the study was to conduct a preliminary desktop classification of South African freshwater fish species based on size – flow guild categories. The primary use of this information will be for consideration during flow requirement studies (such as reserve determinations). Other information that may be of importance during flow requirement assessments, such as the relative size of adults and well as body shape and depth are also provided. It must be emphasised that this is a baseline desktop classification utilizing readily available information. This database should be updated and expanded in future by specialists of specific fish species or groups, as well as when more information becomes available on specific aspects of a species.

Furthermore, it must be noted that this database and the definitions of the guilds are still not finalised. Further work will be required by Dr Kleynhans to formalise the definitions and, based on this, the database will be adjusted.

2.5.2 Approach and methodology

Readily available literature was used to determine the general maximum total length (TL), life stage history and/or biology of South African freshwater fish species. Emphasis was placed on the gathering of information regarding the preference or tolerance of a species for specific habitats in terms of flow (lotic or lentic). Intolerance ratings of each species in terms of its "requirement for flow" as well as preference ratings for specific velocity-depth (SS, SD, FS and FD) (Kleynhans, 2003) were also considered in the determination of habitat preference and flow dependence of species (although these ratings are primarily applicable to the adult stage). A broad estimation was also done of the body shape as well as body depth of each species. This information is important when considering water depths for the purpose of spawning, connectivity (especially for migration) during environmental water requirement assessments.

2.5.2.1 Size (Length) category

Each fish species was classified into a specific size category, based on the following ranges (From Kleynhans, 2008):

Small size category: <150 mm total body length;
Intermediate size category: 150 to 250 mm total body length; and
Large size category: >250 mm total body length.

- If information was only available as standard length, an estimation of the expected total length was made.
- If the known maximum total length fell on the border of a category, it was assumed that most adults will fall on average in the smaller of the two categories, and therefore the fish was categorised as such.

2.5.2.2 Fish Flow guilds

A guild is a group of species that exploits the same environmental resources (e.g. habitats) in similar ways (Root 1967). Therefore, all members of a guild should be affected by the alteration of those resources (Roberts and O' Neil 1985). Fish guilds often described in literature include habitat guilds, feeding guilds or reproductive guilds. The objective of this fish guild classification is for use of fish in environmental flow requirement studies. For that reason, the approach followed during this study aimed at prioritising aspects that are important in setting flows for fish, with the most important criterion considered to be "their requirement for flowing water", and this classification is therefore referred to as "flow guilds". The "flow guilds", used for the purpose of this study and a description of their characteristics are as follows:

a) Rheophilics
Fish species where all freshwater life stages are confined to lotic waters. They require flowing water during **all phases** of the life-cycle. These species prefer strong flow and clear water, using this habitat both for breeding and feeding.

b) Eurytopic (Semi-rheophilic)
All life stages can occur in both lentic and lotic waters (often require lotic habitats for at least one life stage, generally reproduction, but other life-stages can survive in lentic habitats). These species can however survive periods of cessation. These species tolerate a wide range of flow conditions. For the purpose of this flow guild classification, eurytopic species were generally considered as those that spend and require flowing water for some life-stages, while other life stages can be completed in slow (lentic) habitats. Flow may still be required to maintain adequate habitat condition (such as good water quality) during these periods. Although the term eurytopic may also be used to refer to species with a wide range of tolerance towards other environmental conditions (see extract below from Welcome et al, 2006), such as water quality, this was not considered during this assessment as this classification was predominantly aimed at **flow** being the primary determinant. For the purpose of flow requirement studies, eurytopic guild can be broadly used as the semi-rheophilic fish guild often referred to during the EWR process.

[Welcomme et al. (2006) states that eurytopic species (generalists) are generalized and extremely adaptable species that are often tolerant of low dissolved oxygen concentrations. They are generally repeat breeders or may breed during both high and low flow phases of the hydrograph, as such breeding may be independent of flow clues. <u>They may have either rheophilic or limnophilic characteristics</u>. They are predominantly phytophils (Obligatory plant spawners with adhesive egg envelopes that stick to submerged live or dead plants), phytolithophils (a reproductive guild of a non-obligatory plant spawner characterised by adhesive eggs scattered on submerged objects, late hatching, cement glands in free embryos, showing photophobia, and moderately developed respiratory structures, e.g. Perca flavescens {Percidae}), lithophils (Rock and gravel spawners), or psammophils (Sand spawners with adhesive eggs, free embryos not possessing cement glands, free embryos with large pectorals, larvae with weekly developed respiratory structures and large neuromasts and phototrophic larvae) but some species are nesters or parental carers. They may be short distance migrants (semi-migratory) often with sedentary, local populations. There is evidence (Bouvet et al., 1985; Linfield, 1985), however, that some species at least have both mobile and static elements in their genome and are thus able to adapt to drastic changes in flow type]

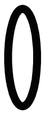
c) Limnophilic
All life stages of these species confined to (prefer) lentic waters. These species prefer to live, feed and reproduce in slow-flowing to stagnant water (body shape generally not suited for flowing water, i.e. tilapias). These species can complete all life stages in lotic or slow habitats and do not require fast habitats for any life stage (such as during spawning).

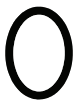
Considerations and limitations of fish guild classifications:
Some grey areas exist where a species may fall within two possible guilds, or where available information is not sufficient to make a high confidence decision. Some fish species will survive and even thrive in artificial habitats, such as dams and canals. This behaviour was excluded from this analyses and emphasis was placed on the general requirements and preferences of a species in untransformed (their natural) habitat. NB: Classification based on optimal habitats (some species may utilize and survive in other than optimal habitats, e.g. yellowfish in dams, but not optimal conditions).

2.5.2.3 Body shape and depth

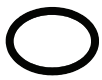
Body shape and depth play an important role in both swimming ability, preference for a specific habitat and especially in water depth required to allow lateral and longitudinal movement or migration. These aspects should be considered in ecological flow requirement studies where applicable.

Body shape:
The general body shape of different species was described as one or a combination of the following body shapes:

Compressed (e.g. Tilapias, etc.) 

Fusiform (e.g. Barbus, Labeobarbus, Labeos, etc.) 

Depressed (e.g. Clarias, Chiloglanis, Amphilius, etc.) 

Anguilliform (e.g. Eels) 

Body depth:
An approximate body depth of an average adult, measured as a cross section in central area from dorsal to ventral area, excluding the fins, was provided by the author, of species that he is familiar with. It must be emphasised that this was estimations and not based on available measured body depths, and will require verification in future.

2.5.3 Results

The preliminary results are provided in an electronic Microsoft Excel Spreadsheet titled SA Fish Flow guilds Ver 2. (Comments are provided and confidence ratings between 1 (low confidence) and 5 (high confidence) is provided regarding the flow guild classification of each species. A copy of the Excel Spreadsheet is provided as Appendix B (on CD at back of this report).

2.5.4 Conclusions

This exercise provided a valuable starting point for classifying the South African freshwater fish species into specific categories based on their size and flow guilds. It must however be emphasised that the classification is preliminary and only based on readily available information. Habitat requirement information is however still lacking for many species, especially early life stages. The categories used for classification (especially flow guilds) were defined and described specifically for the purpose of this assessment, with the main aim to be used in ecological flow requirement studies. The main use would be in selecting the most appropriate indicator species to be used when setting flows. In general their priority would be as follow: Large rheophilic > intermediate rheophilic > small rheophilic > large eurytopic > intermediate eurytopic > small eurytopic > large limnophilic > intermediate limnophilic > small limnophilic.

2.6 INVERTEBRATE APPROACH (DR M UYS, LAUGHING WATERS)

2.6.1 Objectives

The objectives of the invertebrate component of the project were to provide input to the Ecological Submodel and to ensure that invertebrate requirements are considered within the revised Desktop Reserve Model.

To achieve this, the following was required:

- To adapt the FFHA model (Kleynhans 2008) by determining appropriate habitat-flow classes and habitat suitability criteria for invertebrates (family level);
- To trial the adapted FFHA invertebrate model by running the model for a number of rivers and sites for which hydrological, hydraulic and invertebrate data were available;
- To investigate means of determining the hydraulic habitat suitability ratings for indicator invertebrates or invertebrate guilds (as a function of river size, taxa, and hydraulic parameters) for different river sizes, substrate types and flow conditions;
- To investigate means of incorporating invertebrate habitat suitability ratings into the revised Desktop Estimation model.

2.6.2 Adapting the FFHA Model for use with invertebrate data

The FFHA was developed for fish. However, the model is generic in terms of loss of habitat suitability from natural and it is only the suitability criteria and the VD classes that are specific to fish. The suitability criteria and VD classes therefore had to be defined for invertebrates to enable the use of this model The FFHA model developed by Kleynhans in 2008 was provided to the invertebrate specialists, and initial brief training was provided in the use of the model.

The FFHA model was developed to assess flow requirements for different sized rivers and different Ecological Categories. The only invertebrate indicator group incorporated initially in the model was cobble dwelling invertebrates. This group comprises any invertebrate families with a preference for cobble habitat and usually have a preference for flow velocities of >0.1 m/s, and more typically, >0.3 m/s.

The fish model incorporates a number of depth/velocity classes appropriate to different fish guilds. Seven substrate / flow-velocity classes had to be included for invertebrates. These are similar to the classes used to assess invertebrate flow requirements in the Ecological Reserve Determination Stressor Response method for South African rivers (O'Keeffe et al 2002):

- SCS – slow flow (0.1-0.3 m/s) over coarse substrates (gravels and larger)
- FCS – fast flow (0.3-0.6 m/s) over coarse substrates
- VFCS – very fast flow (>0.6 m/s) over coarse substrates
- SFS – slow flow over fine substrates
- FFS – fast flow over fine substrates
- SBB – slow flow over bedrock
- FBB – fast flow over bedrock

Where hydraulic cross-sections are surveyed at a river site during two successive sampling trips (low and high flows), these data are used to calculate the percentage cover of these different flow classes for the cross-section at the measured discharges. Percentage cover values for the cross section are then interpolated for the full range of low-flows (*"Hydraulics look-up tables" provided by Dr, A.L. Birkhead*). Thus, for each of the river sites included in this study, all percentage cover values for the 7 substrate / flow-velocity classes were available as inputs (to *Hydra Spreadsheet in FFHA*).

Rapid Level III-type hydraulic information was provided for selected sites. This included the prediction of the spatial availability of the flow-classes provided above. These were then used as inputs to the Hydra Spreadsheet in FFHA.

The Hydraulic Habitat Suitability Criteria (on the "FFH Spreadsheet" of the FFHA model) were also altered for the invertebrate data. Five hydraulic habitat suitability criteria were elected for invertebrates:

- Diversity
- Abundance
- Suitability and physical quality
- Connectivity
- Chemical quality.

2.6.3 Input of invertebrate data

The adjusted model was then trialled in an exercise designed to generate, for A-D Ecological Categories, drought and maintenance flow (and stress) requirements for invertebrates in the wet and dry seasons. This exercise made use of existing hydrological, hydraulic and invertebrate data for the calibration sites listed in 2.1.

2.6.4 Hydraulic habitat suitability ratings for indicator invertebrates

It was decided at a workshop on 22 February 2010 that the initial requirement for ecological input to the Revised Desktop Model would be a first-attempt at generic hydraulic habitat suitability ratings for fish guilds and for invertebrates (FDIs only). These ratings were required for different river sizes, and should be a function of river size, guild / taxa, and hydraulic parameters / flow classes (Chapter 3). An explanation would be provided of how the suitability ratings are used within FFHA to provide the flow requirements for the different Ecological Categories.

There are a number of constraints in this regard, for the invertebrate specialists:

- Whereas South African fish species' habitat preferences are fairly well understood, even at the level of different life-history-stage requirements, this is not the case for invertebrate species of SA Rivers. Preferences of different invertebrate families for particular classes of flow velocity, types of habitat / substrate, and water quality condition have been rated (using a scale of increasing preference from 0 to 5) at a preliminary level by Thirion et al. at DWA:RQS. Extensive further research and data-enquiry is however required to present invertebrate habitat preferences with confidence. This is the subject of a PhD currently underway by Thirion (DWA:RQS).
- As yet, no depth preferences have been assessed for invertebrates as they have for fish. The Israeli team of Degani et al. (1993) have investigated depth requirements of selected macroinvertebrate taxa, and report clear depth-range preferences for certain taxa. These data have yet to be verified for South African rivers and macroinvertebrates.
- The requirement was to provide habitat suitability ratings based on velocity and depth. This was inappropriate to invertebrates, as depth preferences are largely unknown as discussed above. There was unresolved discussion amongst project team members regarding the inclusion of substrate in the invertebrate habitat suitability criteria and ratings, following the HABSPECS (habitat preference rules) approach followed by Birkhead in the earlier WRC Estimation Study (WRC KV210/08).

A short workshop to develop habitat suitability ratings was planned with a number of invertebrate specialists representing the country's different provinces. This was considered critical to get the most comprehensive and valid information possible per river type and invertebrate indicator group.

In the interim, discussion between the invertebrate, fish and hydraulic specialists on the Project Team, supported by a review of international literature, led to the decision that this workshop would be premature and that a great deal more literature review and preparation would be required to achieve the objectives. Only two of the specialists (Thirion and Uys) had any knowledge of the concept being developed, and of the FFHA model. It was felt that within this project, a number of basic issues still needed to be clarified before involving external parties.

2.6.5 Conclusion

Before the development of any habitat suitability ratings for invertebrates, the following critical thinking is required:

- A rigorous assessment by invertebrate specialists of whether or not it is valid ecologically and biologically for the invertebrate and fish sub-models (for the revised Desktop) to follow the same approach, bearing in mind that – inter alia – the relevance of depth is entirely different for fish than for invertebrates. For the latter, flow-related depth is only instructive in that it enables one to assess whether or not flow covers the critical substrate or vegetation type, and therefore whether or not it activates important habitat. Depth is not yet a suitable criterion to use in assessing invertebrate habitat suitability.
- Consideration of whether one invertebrate "guild" (Flow Dependent Invertebrates) is adequate, or whether there should be division of this into a number of groups with more specific, definable hydraulic habitat preferences.
- Whether or not the HABSPECS approach can be followed within the sub-model. Substrate is a critical aspect of habitat for invertebrates and there has not yet been adequate discussion within the team to address this issue.
- The later development of the VDG model causes similar problems for adjustment for use for invertebrates and will also have to be addressed according to the above issues.

It was therefore concluded that for the first phase of the revised Desktop Model, invertebrate requirements cannot be included. The above issues must be addressed in detail and it is hoped that during the refinement phases of the revised Desktop Model, invertebrates can be included.

2.6.6 Conclusions & recommendations

The VDG model developed for fish must be coded and tested for appropriate sites where comprehensive Ecological Reserve EWRs are available.

The inclusion of invertebrates must be undertaken during a potential next phase of the study.

3 THE DEVELOPMENT OF THE HYDRAULICS SUB-MODEL

The development work for the hydraulic sub-model was undertaken by Mr Ahmed Desai as part of his PhD research under the supervision of Prof Denis Hughes and Dr Andrew Birkhead. This part of the project represented a great deal of background assessment of previous hydraulic results generated as part of Reserve studies. These assessments were used together with the project teams 'conceptual' ideas to develop the hydraulic parameters that form a key component of the hydraulic sub-model and the generation of desktop channel cross-sections. This part of the report includes extracts from Mr Desai's thesis, which is expected to be available during early 2012. The thesis contains an extensive literature review that is not repeated here but which supported the development of the sub-model

The objective is to produce a hydraulic sub-model that is appropriate for inclusion in the RDRM that will provide the essential links between the ecological sub-model (habitat requirement – Reserve category rule base) and hydrological scenarios. The design of the hydraulic sub-model should use the hydrological information and the hydraulic characteristics of the area under investigation to produce hydraulic habitat information for use by the ecological sub-model. As a desktop study, the hydraulics sub-model will not use any field hydraulic surveys and the hydraulic characteristics will be estimated from readily available physical variable or data for South Africa.

The basic design principles of the hydraulic sub-model are that it should produce a realistic representation of the hydraulic conditions through ecohydraulic modelling procedures using hydraulic parameters and characteristics estimated from readily available information for any part of the country, with a "reasonable" degree of certainty.

The following three basic principles have been established on the basis of the essential requirements for a desktop Reserve determination model and the need to incorporate more of the emerging science of environmental flows:

1. The model should be able to translate habitat requirements as defined by the ecology sub-model (the assumption is that these will be defined as frequencies of different velocity-depth classes) into discharges, which can then be used by the hydrology sub-model to define flow requirements.
2. The input data requirements should be based on readily available information that can be accessed from existing databases (numerical, GIS or map information) relating to topography, geomorphology, geology and possibly vegetation.
3. The model should be flexible in the way in which it is run. This means that under normal circumstances the user would not see the details of the model but only the output (i.e. the model operates as a 'black box' with default regional parameters). However, the computer code must allow for 'intelligent' user intervention where some, or all, of the default regional input data can be over-ridden by the user. This is in line with the current version of the Desktop Reserve

model and allows the model to be used for different levels of Reserve determination.

3.1 DATA REQUIREMENTS AND PARAMETER ESTIMATION

Ecohydraulics results have been generally provided as look-up tables relating discharge to ecologically relevant hydraulic parameters; maximum and average depth, width, perimeter, average and maximum (99.5% on the Lamouroux *et al*., 1995 distribution) velocity, as well as the relative spatial composition of hydraulic and biophysical conditions defined using flow classes for fish and invertebrates. The starting point in order to generate these hydraulic parameters and flow classes would be to generate a representative cross–sectional (XS) profile. The main characteristics of the XS are generated on the basis of the following model parameters:

- Maximum channel width (m).
- Maximum channel depth at bankfull (m).
- Channel shape (e.g. rectangular/trapezoid, parabolic, v-shaped).
- The % of the maximum width if the channel shape is rectangular or trapezoid.
- Macro roughness size (m) defining the large roughness elements that make up the cross-section (typically large boulders and rock outcrops, or other variations in the cross-section).
- Micro roughness size (m) defining the smaller scale roughness elements that make up the cross-section (typically cobbles, coarse sediment or fine sediment).

The next step would be to generate a representative rating curve (relationship between water depth and discharge). It was decided to use the Manning formula and the generated XS to produce the rating curve; thus Manning n and slope were required as model parameters.

The parameters required for generating the XS and the rating curve were obtained through the development of estimation equations. The selection of appropriate variables for the estimation equations was based upon the 2nd design principle that the variables should be generally available and that site specific investigations should not be required to quantify them. Several sources of information were identified and are listed below. Reviews into the availability of datasets for these variables were undertaken and the datasets selected for use (see bolded items) in the development of the hydraulic sub-model are discussed in Section x.2.

The types of variable that were expected to affect the channel XS shape were:

- Topographic (generally available from topographic maps or DEMs, including:
    - Position in the hydrological landscape (headwater, mid-reach or downstream reach).
    - Local longitudinal gradient.
    - Degree of incision.
    - Valley XS profile shape.
- Geological (generally available from geological maps), including:
    - Some measures of rock hardness.

  - Some measures of rock fracturing characteristics.
  - Sediment load characteristics (from previous sediment load studies).
- Hydrological (available from regional hydrology such as WR90 or WR2005), including:
  - Mean or median annual runoff.
  - Mean annual flood.
  - A measure of hydrological variability.
  - Other hydrological measures based on flow duration curve percentage points.
- Vegetation (availability uncertain), including a measure of dominant riparian vegetation and its effect on bank stability.

The types of variables that are expected to affect depth-roughness relationships are:
- Substrate type, in turn related to:
  - Geology (see above).
  - Sediment load (see above).
  - Channel size and gradient (see above).
  - In channel vegetation (see above – data availability uncertain).

The types of variables that are expected to affect depth-energy slope relationships are:
- Topographic and/or geomorphological, including:
  - Broad channel types and the sequences of pools, runs and riffles.
  - Known geomorphological characteristics of rivers (Rowntree and Wadeson, 1999)

3.2 PHYSICAL VARIABLES AND OTHER SOURCES OF INFORMATION

The initial expectations were that the physical variables could include measures of topography, geology, geomorphology, hydrology and vegetation cover. Reviews into the availability of various physical variables were undertaken and the following data sources were selected for use in the development of the estimation parameter relationships and the hydraulic sub-model.

- **Topography**

Topographic data are readily available from maps and digital elevation models. The usefulness of the data source depends upon the resolution and accuracy of the data and the ease with which it can be subject to automated analysis to derive valley slopes, etc.

- **Hydrological**

Hydrological data form part of any Reserve study and may consist of regional datasets such as WR90 or WR2005 or specific simulations of the natural and present day hydrology. However, these data sets do not contain information about flood peaks and likely channel forming discharges.

- **Geomorphological**

Rowntree and Wadeson (1998) have developed a zonal classification system for South African rivers modified from Noble and Hemens (1978). Moolman et al. (2006) attempted to give each zone a geomorphological definition in terms of distinctive channel morphological units and reach types. After working in a diverse range of rivers around the country it became clear that channel gradient is a good indicator of channel characteristics and that probable or expected differences can be identified from an analysis of gradients. Based on the Rowntree and Wadeson (1999) classification, the geozones for the country have been mapped. While Rowntree and Wadeson (1999) used the river channels and contours from 1:50 000 map sheets, Moolman et al. (2006) used the river channels of the DWAF 1:500 000 river coverage (adjusted to within 50 m of 1:50 000 rivers) and a 20 x 20 m resolution Digital Elevation Model (DEM) (derived by Computamaps from contours at 20 m intervals). The geozone classifications derived are tabulated in Table x.1

- **Hydraulic Database**

A hydraulics database of past EWR studies was developed by Birkhead and Desai (2009). The database consists of hydraulic and related information of 359 EWR comprehensive, intermediate and rapid Reserve sites. The following parameters from the database are of significance to this project:

  - Runoff – Natural Mean Annual Runoff (nMAR) (106 m^3 y-1) – obtained from WR90 or WR2005 and scaled to the EWR site location. Scaling was done on a catchment area basis.
  - Site Location – latitude, longitude, altitude.
  - Geozone – A to F (Table 3.1).
  - Sediment types and/or sizes.
  - Hydraulic Data – Discharge, Q (m^3/s), Maximum flow depth, y (m), Average flow depth, yav (m), Cross-sectional flow area, A (m^2), Inundated width, W (m), Wetted perimeter, P (m), Average velocity, V (m/s), Inundated width (W) for maximum flow depths (y) of 0.10, 0.20 and 0.30 m, Water surface slope, S (m/m), Valley slope, VS (topographical map or similar), Manning's flow resistance coefficient (n), Rating curve coefficients (a, b and c, with a maximum of three curves allowed)

Measured XS data were obtained from various hydraulic or management consultants that were involved in the past EWR studies.

Table 3.1 Geomorphological Zonation of River Channels (after Rowntree and Wadeson, 1999)

Longitudinal Zone	Macro-Reach Characteristics		Characteristic Channel Features
	Gradient Class	Zone Class	
Mountain headwater stream	>0.1	A	Very steep gradient dominated by vertical flow over bedrock with waterfalls and plunge pools. Normally first or second order.
Mountain stream	0.04-0.99	B	Steep gradient dominated by bedrock and boulders, locally cobble or coarse gravels in pools. Reach types include cascades, bedrock fall, step-pool, Approximate equal distribution of 'vertical' and 'horizontal' flow components.
Transitional	0.02-0.039	C	Moderately steep dominated by bedrock or boulder. Reach types include plain-bed, pool-rapid or pool riffle. Confined or semi-confined valley floor with limited flood plain development.
Upper Foothills	0.005-0.019	D	Moderately steep, cobble-bed or mixed bedrock-cobble bed channel, with plain-bed, pool-riffle or pool-rapid reach types. Length of pools and riffles/rapids similar. Narrow flood plain of sand, gravel or cobble often present.
Lower Foothills	0.001-0.005	E	Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may be bedrock controlled. Reach types include pool- riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present.
Lowland river	0.0001-0.001	F	Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering pattern within a distinct flood plain develops in unconfined reaches where there is an increased silt content in bed or banks.

3.3 CALIBRATION AND ESTIMATION OF HYDRAULIC PARAMETERS

The hydraulic parameters necessary to produce the representative hydraulic information for the hydraulic sub-model were calibrated against the hydraulic database of past EWR studies (Birkhead and Desai, 2009). The calibrated model parameters were then used with the physical variable databases to develop estimation relationships through standard multiple regression type procedures and using the hydraulic parameter estimation relationships identified from a literature review as a guide.

The calibration and regression exercises revealed that the relationships to estimate the hydraulic parameters contain various uncertainties due to the complex interaction between the hydraulic parameters resulting in values of some parameters being related to values of the other parameters for the wrong reasons (i.e. the concept of equifinality in complex models) and 'operator error' (discussed later). This resulted in substantial scatter between the parameters and moderate to weak correlations were achieved. Therefore an alternate, conceptual, approach was adopted to achieve pragmatic estimates of the hydraulic parameters. In the conceptual exercise, the hydraulic relationships to estimate the hydraulic parameters for the RDRM were developed based on physical characteristics/theory, sound theory and various assumptions using past experience and conceptual sense and partly guided by the calibration and regression results.

The hydraulic sub-model parameters were calibrated against previous EWR studies through the development of a ‘calibration’ software program which facilitated the processing of the large amount of data and generated appropriate parameter values that were used in the estimation exercise. A screenshot of the calibration program is illustrated in Figure 3.1. The calibration programme included a facility to import, as simple text files, the observed XS profile (elevation vs. chainage) and the rating curve (depth vs. flow). The rating text file was generated using the rating coefficients (a, b & c) from the hydraulic database (Birkhead and Desai, 2009) and the rating equation.

The first step in the parameter estimation process was to specify the maximum depth that will be used and the program defines the basic shape and draws this in red (top left hand graph) superimposed onto the observed cross-section. If an inappropriate maximum depth was specified, it was a simple matter to repeat this process until a sensible basic shape was drawn. The basic shape could be parabolic or v-shaped or rectangular with varying bed widths (as a % of total width). The program decides on the ‘best’ basic shape by comparing all possibilities with the observed cross-section. A minor alteration was included, during the initial calibration exercise, which involved allowing for a non-symmetrical shape to allow for greater accuracy in the reproduction of the observed cross-section shape. Effectively this meant that the when the initial shape is determined the channel bottom could be offset from the centre of the channel. This had very little effect on the way in which the rating curve was optimised, but did have an effect on fitting the channel parameters, i.e. width and roughness (macro and micro) elements. Figure 3.2 illustrates the differences in shapes (Yellow line = before and Green lines = after).

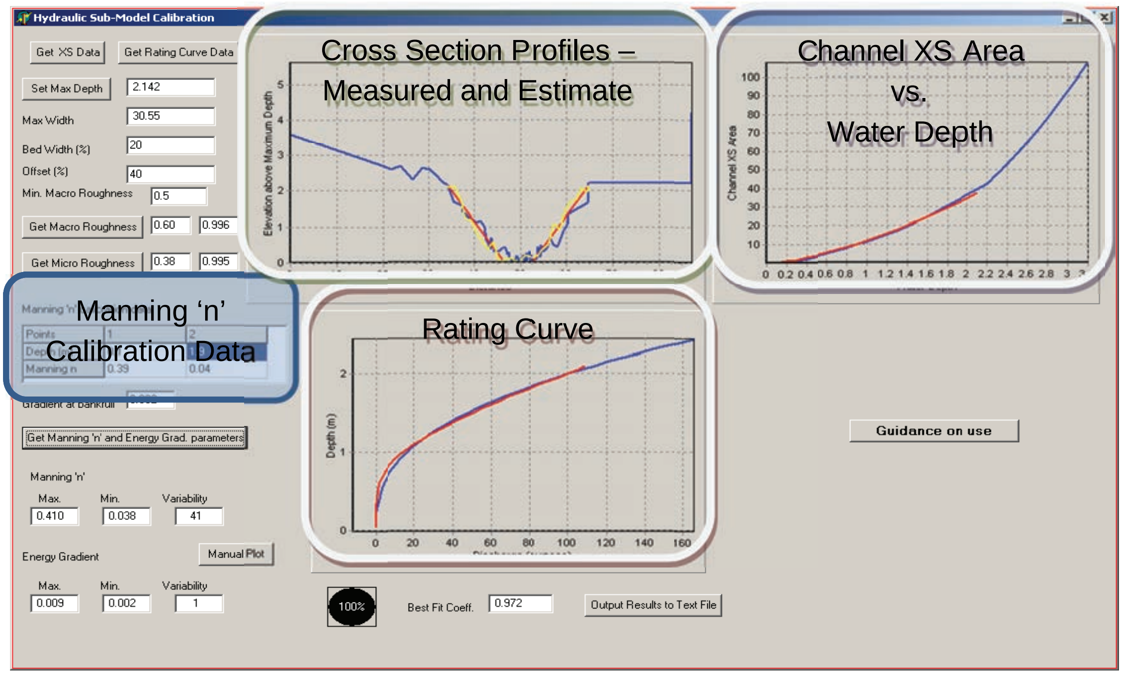


Figure 3.1 ‘Calibration’ program for the parameters of the test version of the model

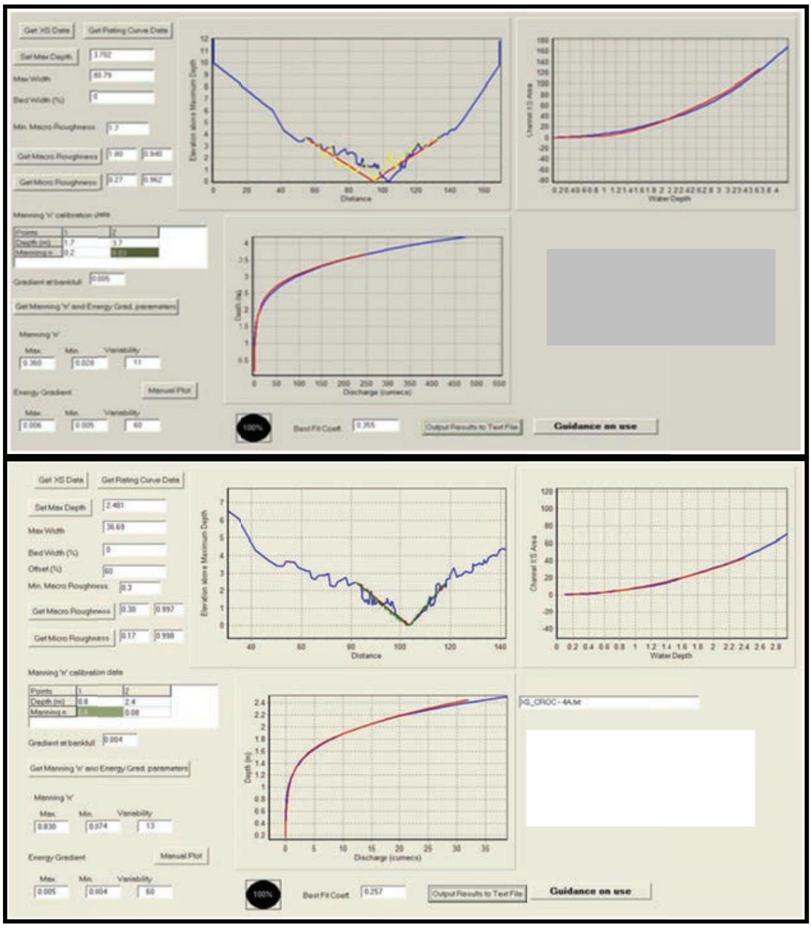


Figure 3.2 Screenshot of the calibration programme for Crocodile River site 4A indicating the difference in estimated XS profile – Top = initial result, Bottom = re-assessment result

The second step was to 'Get Macro Roughness' which is the parameter that defines the large scale roughness elements that make up the cross-section (typically large boulders and rock outcrops, or other variations in the cross-section). The calibration program uses a random number generator to quantify the variations in roughness and optimizes the maximum roughness by checking the differences with the observed cross-section. The same process is repeated with the 'Get Micro Roughness' process and the objective function (coefficient of efficiency – maximum value = 1.0) values are given in the text boxes adjacent to the boxes used to display the roughness values (to the left of the graph). Repeated clicks on the buttons revealed the extent of the uncertainty in the determination of these roughness values, as a different random sample was generated each time. If the values changed a lot with each click, then there was a lot of uncertainty about the best values to use. If they vary very little, there was less uncertainty. The graph at the top right illustrates the relationship between water depth and cross-sectional area for both the observed and estimated cross-sections. The objective was to achieve a good representation of the observed relationship.

The next part of the process was to establish the relationships between Manning's 'n' and the energy gradient and water depth that are used in the model to determine the rating curve. This was a relatively complex process requiring additional user intervention, mainly because establishing an appropriate parameter set is difficult without first establishing some boundary conditions for the estimation equation.

Figure 3.1 shows the table for Manning 'n' calibration data that allows the user to specify two Manning 'n' values for two water depths and the energy gradient at bankfull. The assumption was made that these values were available from the field work undertaken during the cross-section survey or later visits to the site. These values could also be derived from a combination of field data and a separate hydraulic model. Ideally, the two depth values should cover the full possible range of depths so that limits of 'n' for the full rating curve can be defined. In the absence of suitable field data, the channel XS characteristics and individual experience were used to quantify the appropriate range of 'n' values.

Below the Manning 'n' calibration data table is a button ('Get Manning 'n' and Energy Gradient Parameters') that starts the optimization process for quantifying the parameters of the relationships for Manning's 'n' and energy gradient variations with water depth. These are both non-linear relationships defined by minimum and maximum values together with a 'variability' parameter that defines the shape of the relationships. The relationships were assumed to be of an S-curve type as illustrated in Figure 3.3 for variability parameter values of 30 and 5.

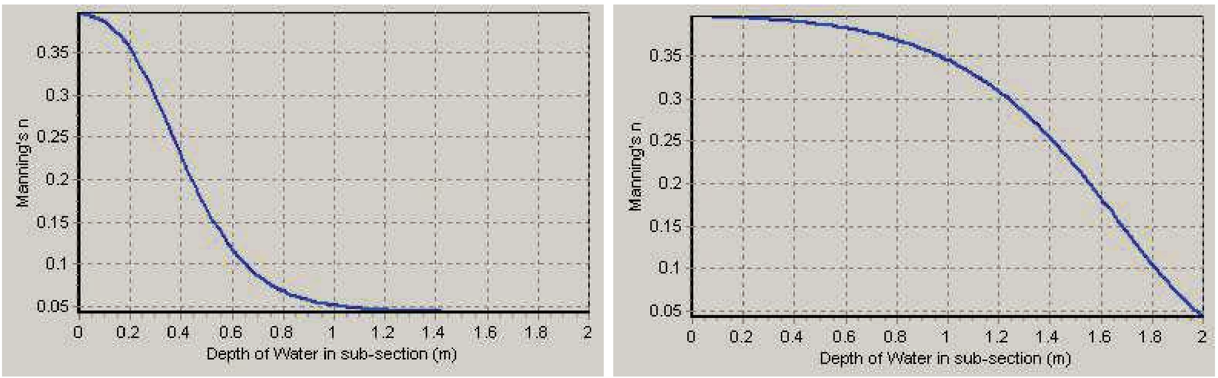


Figure 3.3 Relationships between water depth and Manning's 'n' for variability parameter values of 30 (left side) and 5 (right side)

The optimisation process attempts to find the best values of the minimum and maximum 'n' and energy gradient values as well as the variability parameters that will generate a rating curve close to the observed rating curve within the calibration data constraints for 'n' and slope. If a poor fit to the observed rating curve resulted, then either the calibration data or the S-curve relationship type was inappropriate. In such cases, investigations into which part of the rating curve fails to fit the observed curve were undertaken to decide on further action.

The objective of running this program was to generate the model parameters so that further investigations can proceed. These further investigations involved the development of estimation relationships between the hydraulic parameters and physical variables or data.

3.4 DEVELOPMENT OF ESTIMATION RELATIONSHIPS

A total of 300 out of the 359 sites from the hydraulic database were used in the calibration programme. Insufficient cross sectional or rating curve information was the reason for excluding the remaining 59 sites. The results indicated that the calibration program can be considered appropriate to guide the calibration process, in that the program reproduced the channel geometry and rating curve characteristics of the observed cross-sections reasonably well. However, the next step (i.e. regression analyses) revealed certain inherent flaws and limitations in the calibration program and the next step in the development of the hydraulic sub-model was to try and establish relationships of the various parameters of the hydraulic sub-model with readily available physical variables or data.

The calibrated sites were sorted according to Geomorphic Zones (A – F) and further portioned into channel shape types (Triangular, Parabolic and Trapezoid). The Trapezoid channel was categorised into three groups (S,M,L) based upon their bed width as a % of maximum width (S = 10-30%, M = 40-60% and L = 70-90%).

3.4.1 Maximum Channel Width (W_{MAX}) Relationships

Figures 3.4 to 3.6 illustrate the relationships between maximum width (W_{MAX}) and natural mean annual runoff (nMAR), mean annual flood (MAF) and catchment area (CArea) respectively. nMAR was obtained from the hydraulic database, MAF was determined using Mkhandi and Kachroo (1997) relationships for South Africa and CArea was digitised, using GIS software, for each EWR site using the location (Latitude & Longitude), 1:50 000 topographical map and Quaternary catchment boundaries. The regression relationships have been fitted to all of the data points, but additional series have been added to the graphs to try and identify if there are any obvious differences in the relationships for different geomorphic zones (B to F). The results suggest no systematic differences between geomorphic zones. Substantial scatter is observed in all three series, with power relations producing moderate correlations.

The power relations and R^2 values are tabulated in Table 3.2 and the relationship between maximum width and mean annual discharge is similar to Leopold & Maddock (1953) hydraulic geometry relationships, with their downstream exponent documented as 0.5.

Table 3.2 Maximum Channel Width Relationships.

Series	Relationship	R^2
W_{MAX} vs. nMAR	$W_{MAX} = 9.9254(nMAR)^{0.3022}$	0.44
W_{MAX} vs. MAF	$W_{MAX} = 5.9149(MAF)^{0.403}$	0.42
W_{MAX} vs. Catchment Area	$W_{MAX} = 5.7839(CArea)^{0.2862}$	0.49

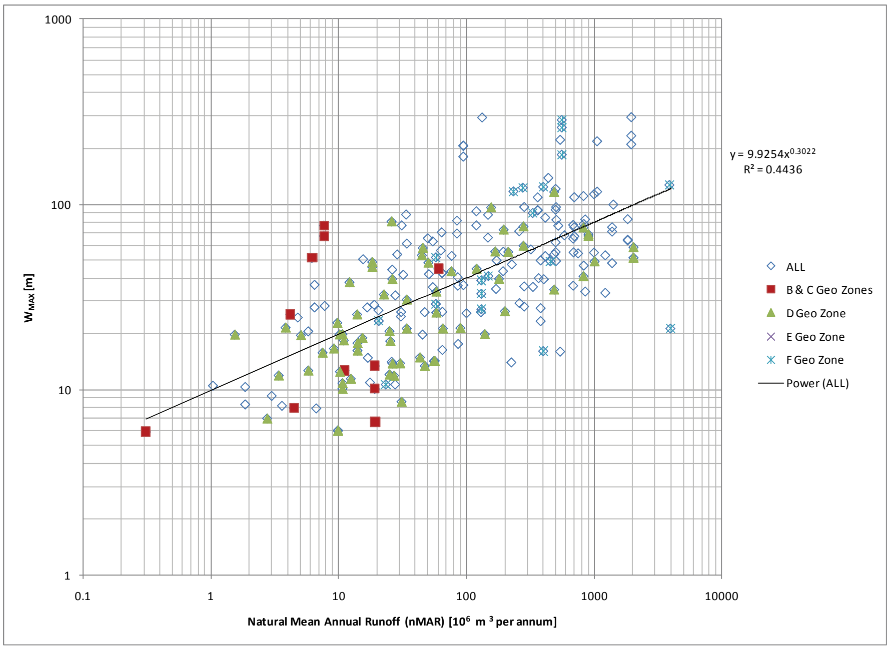


Figure 3.4 **Relationship between Maximum Width (MaxW) and Natural Mean Annual Runoff (nMAR).**

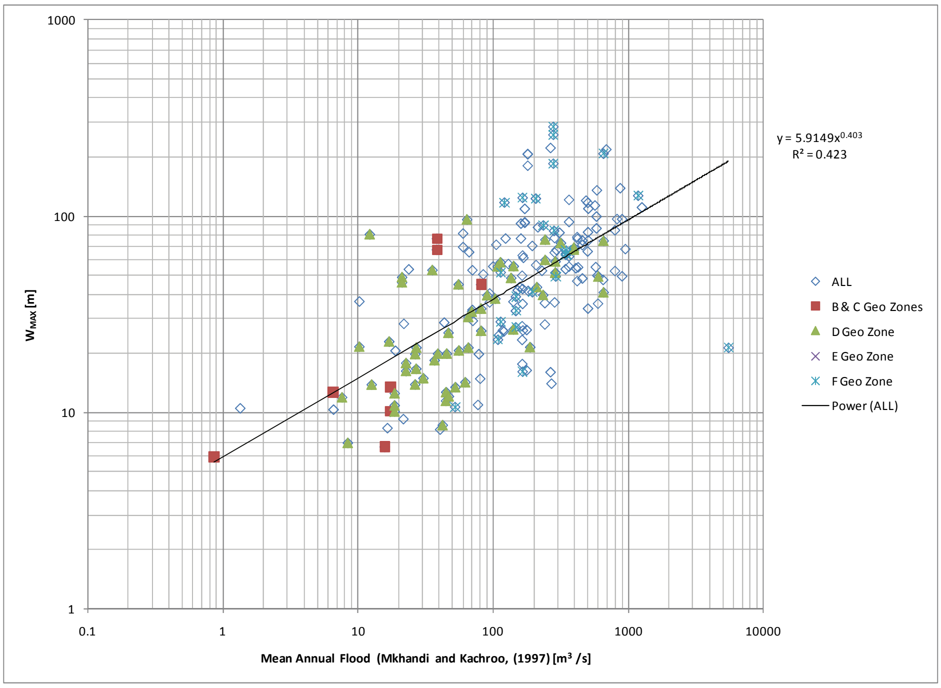


Figure 3.5 **Relationship between Maximum Width (MaxW) and Mean Annual Flood (MAF)**

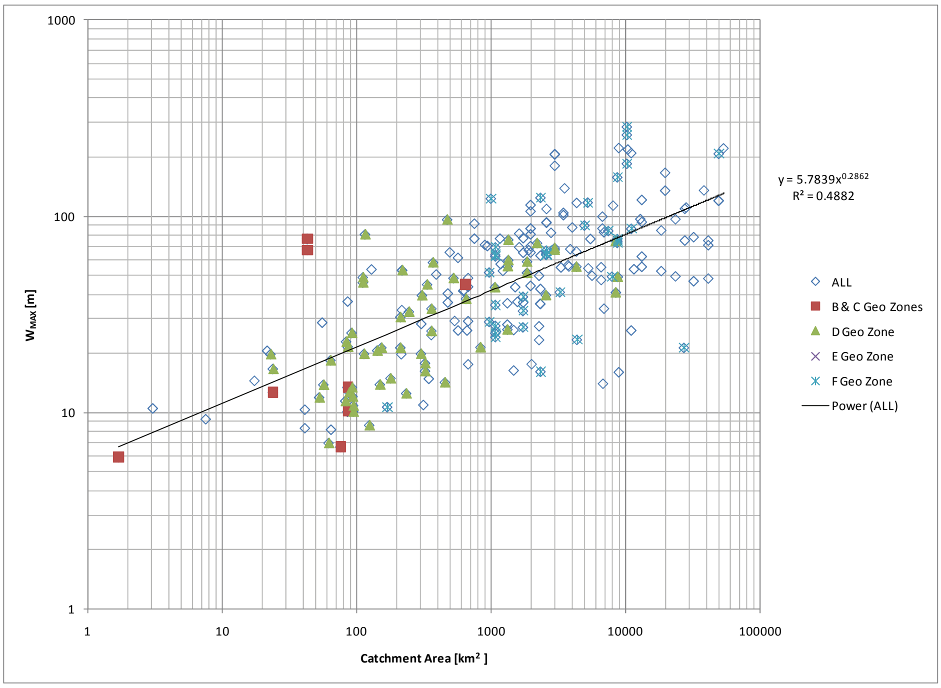


Figure 3.6 Relationship between Maximum Width (MaxW) and Catchment Area

The scatter observed in these relationships may be attributed to the complex interaction of the hydraulic parameters and/or a source of 'operator' error. During the calibration exercise, the selection of a maximum flow depth was based upon the user's choice of what was deemed to provide a sensible depth that would result in bankfull flow and to achieve a sensible channel shape. However, the observed cross-section may not have been fully surveyed, while other surveys may have only concentrated on the low flow channels – thus providing inadequate information to identify a reasonable flow depth. The identification of bankfull depth, from a geomorphological perspective, is not a simple matter; particularly when terraces are present that might be un-related to present day flow regimes. The algorithm to determine the shape of the channel was based upon the observed cross-section points and thus the user may have been forced to select a flow depth that is not representative a bankfull flow, which results in the incorrect maximum width being determined.

Power relationships between W_{MAX} and nMAR (R^2 = 0.44), MAF (R^2 = 0.42) and CArea (R^2 = 0.49) were determined during the calibration exercises. Although the correlations were statistically significant, less than 50% of the variance was explained. However, they produced similar trends that have been observed by researchers in the development of hydraulic geometry parameters. Following the trend of the hydraulic geometry literature, the power relationship between W_{MAX} and some measure of channel forming discharge was adopted.

Jonker & Shand (2010) observed that various studies have found that bankfull discharge displays a consistency in terms of frequency of occurrence, with recurrence intervals of between 1 and 4 years for perennial rivers. However the bankfull discharge does not represent the dominant discharge related to channel form in drier climates, as the river rarely achieved bankfull level for significant periods of time. For these ephemeral rivers, characterised by infrequent high flood peaks, it has been suggested that channel form is related to higher, less frequent events (such as the 1 in 10 year flood), which do not necessarily correspond to the bankfull discharge. This implies that hydrology and climate are important considerations for determining the effectiveness of floods to maintain channel form (Jonker & Shand, 2010). In addition to regional mean annual flood parameters developed, Mkhandi and Kachroo (1997) produced flood frequency curves for the 13 South African regions and noted a more-or-less linear relationship between floods up to return periods of approximately 10 years with the 10 year event (Q_{10}) being approximately 1.8 times the mean annual flood ($\bar{Q}$) across all the regions.

This study has assumed that the maximum width will be represented by the width related to a channel forming discharge (Q_c) where Q_c will vary between $\bar{Q}$ and Q_{10} depending on the aridity and hydrological variability – with more hydrologically variable regions having a Q_c close to Q_{10} and less variable regions having a Q_c close to $\bar{Q}$ (as reported by Jonker & Shand, 2010). A hyperbolic tangent function representing an S-curve shape was used to calculate the ratio of Q_c / $\bar{Q}$:

$$\boldsymbol{x = \left\{tanh\left[4 \times \left(\frac{hydro\_var}{50.0} - 0.5\right)\right] + 1.0\right\} \times 0.4 + 1.0} \qquad 3.1$$

This results in a range of values between 1.0 and 1.8 for $hydro\_var$ values in the range of 1 to 50. The $hydro\_var$ estimate is based on the same hydrological variability index used in the existing Desktop Reserve model (Hughes & Hannart, 2003) and based on coefficients of variability and the baseflow index (calculated from the natural hydrology time series). W_{MAX} is then calculated from the power equation:

$$\boldsymbol{W_{MAX} = aQ_c{}^b} \qquad 3\text{-}2$$

where the coefficients a and b were calibrated against the measured cross-section profiles during the validity and refinement exercise.

3.4.2 Cross Sectional Shape

Three types of cross-sectional shapes, Triangular, Trapezoid (with different bed widths) and Parabolic, were used in the calibration program. It was hypothesised that the shape of the channel would be predicted based upon the geozone, however no systematic differences between geozone and shape could be found. Regression relationships between the cross-sectional shape and the physical variables (e.g. valley slope) and/or other parameters (e.g. W_{MAX}) were undertaken but only weak and generally non-significant correlations (R^2: 0.15 – 0.25) were achieved.

The weak correlations have been attributed to the use of the three shape options in the calibration program. It was found that very little difference could be identified between triangular, parabolic and trapezoids of 10-30% bed widths. Figure 3.7 illustrates the effects on shape when the maximum depth is slightly changed. This high sensitivity of the channel shape to the selection of the maximum depth (and therefore the top of the banks of the channel) results in very similar channel cross-sectional characteristics but different shapes.

Monadjemi (1994) indicated that the most widely used hydraulic section is a trapezoid. It was thus decided to adopt a trapezoidal shape with different bed widths based on geozone (Table 3.3). The divisions of the geozones were based upon the results of the calibration exercise that produced certain bed widths in certain geozones, with anomalies being related to the site selection process that occurs in Reserve studies (i.e. finding 'riffle' sites in lowland rivers that may not be representative of the geozone as a whole). The result of estimating a trapezoid shape with varying bed width based on geozone is that headwater channels tend towards triangular (low bed width), while lowland rivers tend towards rectangular (high bed widths).

Table 3.3 Bed widths defining channel shape according to Geozone

GEOZONE	A	B	C	D	E	F
% BED WIDTH	10	10	10	30	50	80

3.4.3 Minimum Gradient (S_{MIN}) Relationships

The gradient requirement in the Manning equation represents the energy gradient. In uniform flow conditions, the energy gradient and bed gradient are equal. When modelling high flows, uniform conditions are assumed and the valley slope is used in the Manning equation. In the calibration exercise, the high flow water gradient was termed minimum slope (S_{MIN}).

The valley slope is measured using a topographic map, or similar source of elevation data, that contains contour lines. A point upstream and a downstream of the EWR site, where consecutive contour lines cross the river, are identified. The river length between these two points is measured. The valley slope is then determined by dividing the river length by the contour interval.

A strong correlation (R^2 = 0.95) between minimum gradient and valley slope was achieved (Figure 3.8) and it was decided that it would be sufficient to use the valley slope as the minimum gradient in the hydraulic sub-model calculations. In the final implementation of the model, the valley slope will be obtained using the intersection between a river channel coverage and a digital elevation model (DEM) with appropriate spatial resolution in a GIS environment.

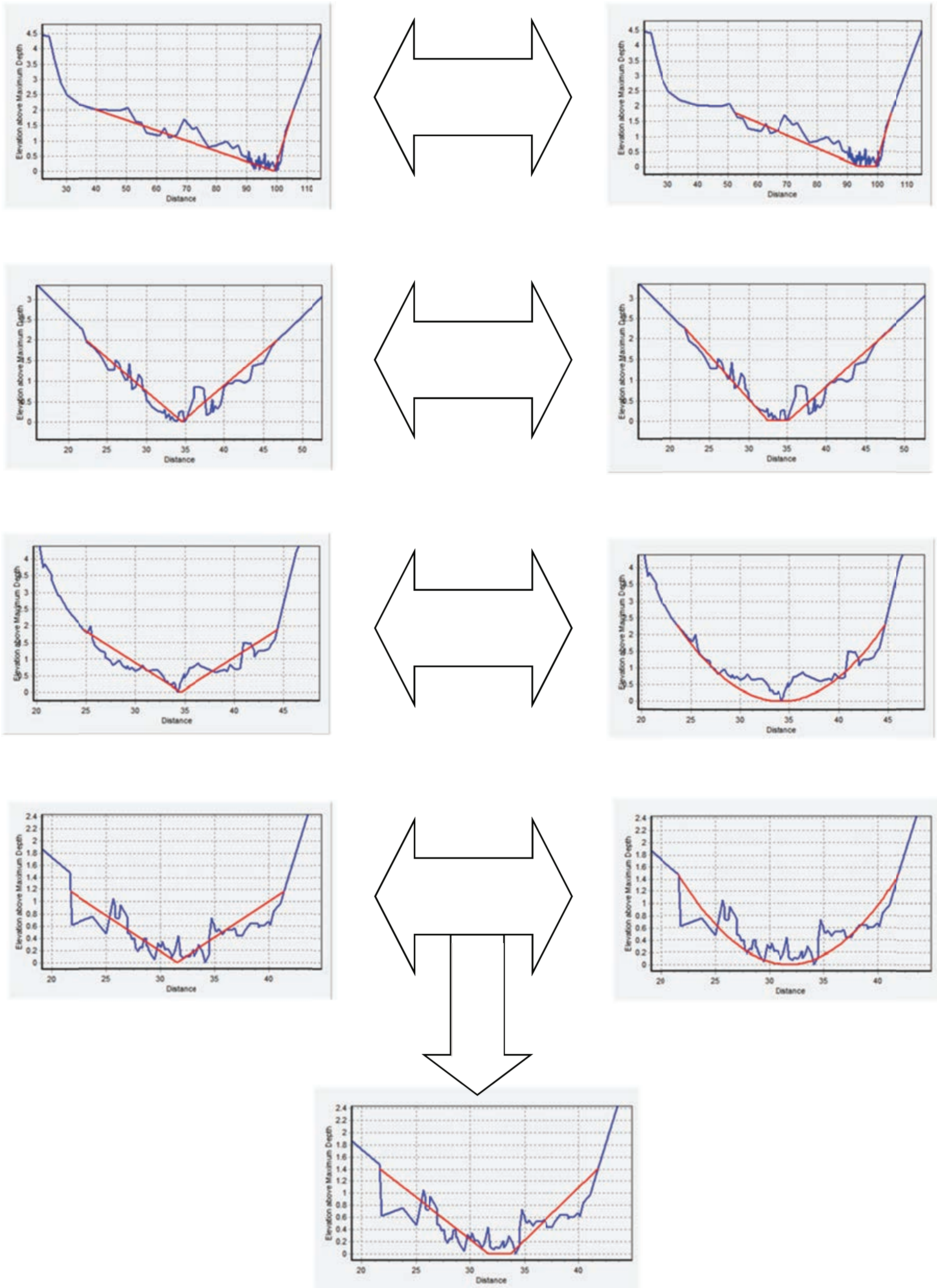


Figure 3.7 Channel Shapes from the calibration program with slight changes in Maximum Depth

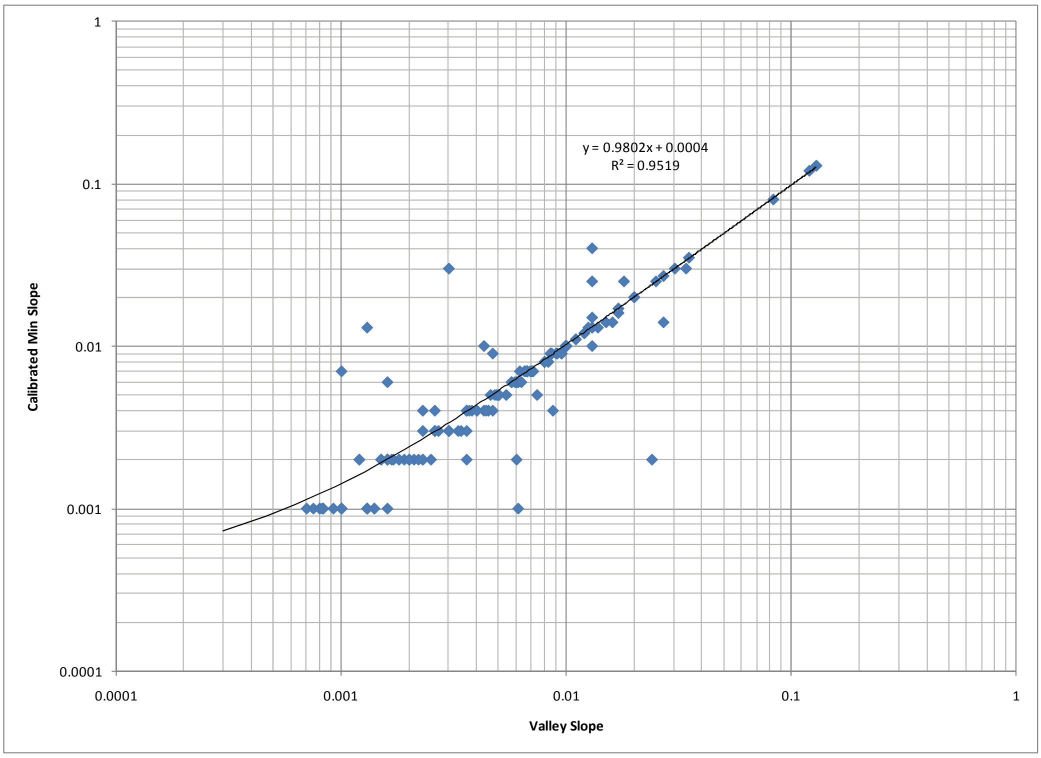


Figure 3.8 Relationship between calibrated minimum gradient and valley slope

3.4.4 Maximum Flow Depth (Y_{MAX}) Relationships

Figure 3.9 illustrates the relationships between maximum depth (y_{MAX}) and maximum width (W_{MAX}) and Figure 3.10 illustrates the relationship between the ratio of W_{MAX} to y_{MAX} and catchment area (CArea). CArea was digitised, using GIS software, for each EWR site using the location (Latitude & Longitude), 1:50 000 topographical map and catchment boundaries. The regression relationships have been fitted to all of the data points, but additional series have been added to the graphs to try and identify if there are any obvious differences in the relationships for different geozones (B to F). The results suggest no systematic differences between geozones. Substantial scatter is observed in both series, with power relations producing moderate correlations. The power relations and R^2 values are tabulated in Table 3.4. The scatter observed may be due to the complex interaction between the hydraulic parameters and/or 'operator' error in selecting maximum width and maximum depth as discussed in the above sections.

Table 3.4 Maximum flow depth relationships

Series	Relationship	R^2
y_{MAX} vs. W_{MAX}	$W_{MAX} = 0.5434(nMAR)^{0.3784}$	0.41
W_{MAX} / y_{MAX} vs. Catchment Area	$W_{MAX} = 4.8661(CArea)^{0.1936}$	0.35

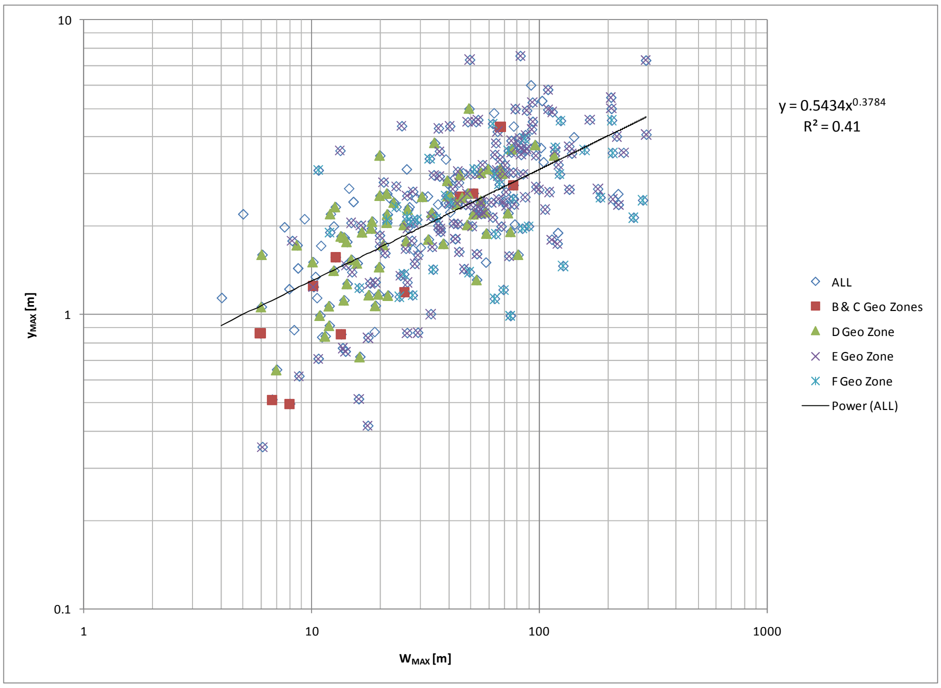


Figure 3.9 Relationship between Maximum Width and Maximum Flow Depth

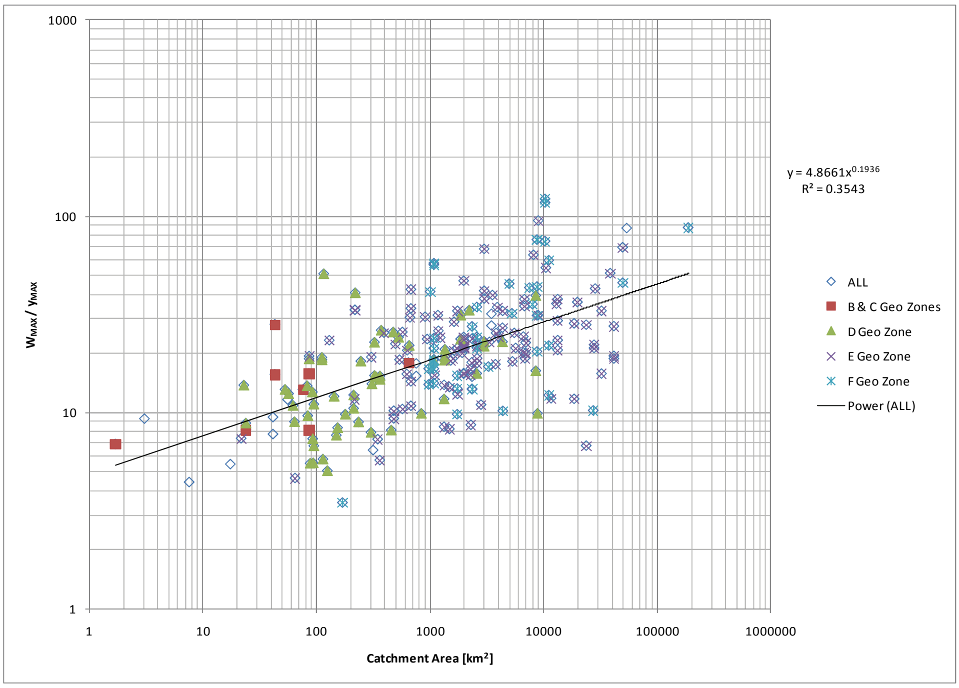


Figure 3.10 Relationship between Width/Depth Ratio and Catchment Area

The parameters, Q_C, WMAX, S_{MIN} and Shape, have already been defined and the maximum depth (y_{MAX}) can therefore be determined by iteratively solving the Manning equation, i.e. $Q_c = \frac{1}{n_{base}} \frac{A^{5/3}}{P^{2/3}} S_{MIN}{}^{1/2}$ for depth. The nominal Manning n (n_{base}) is assumed to be a value appropriate to the channel forming discharge (Q_c) varying from 0.025 to 0.05 for typical natural river streams (Chow, 1959; Barnes, 1967; Hicks and Mason, 1998; Desai, 2007).

The variation of nominal Manning n is based upon the geozone and previous experience from the hydraulic database; the nominal Manning n values used are tabulated in Table 3.5.

Table 3.5 Nominal Manning n for Channel Forming Discharge (Qc) according to Geozone

GEOZONE	A	B	C	D	E	F
Nominal Manning n (n_{base})	0.050	0.040	0.035	0.035	0.030	0.025

3.4.5 Maximum gradient (S_{MAX}) Relationships

During low flows, the water surface gradient is generally steeper than the valley slope. The low flow water surface gradient is required to estimate the low flow portion of the rating curve. In the calibration exercise, the low flow water gradient is termed maximum gradient (S_{MAX}). Figure 3.11 illustrates the relationship between the minimum gradient and maximum gradient values obtained from the calibration exercise. The regression relationship has been fitted to all the data points, resulting in a moderate correlation (R^2 = 0.46). The data points were found to be contained within two linear functions (i.e. upper and lower – see Figure 3.11). The three relationships are tabulated in Table 3.6.

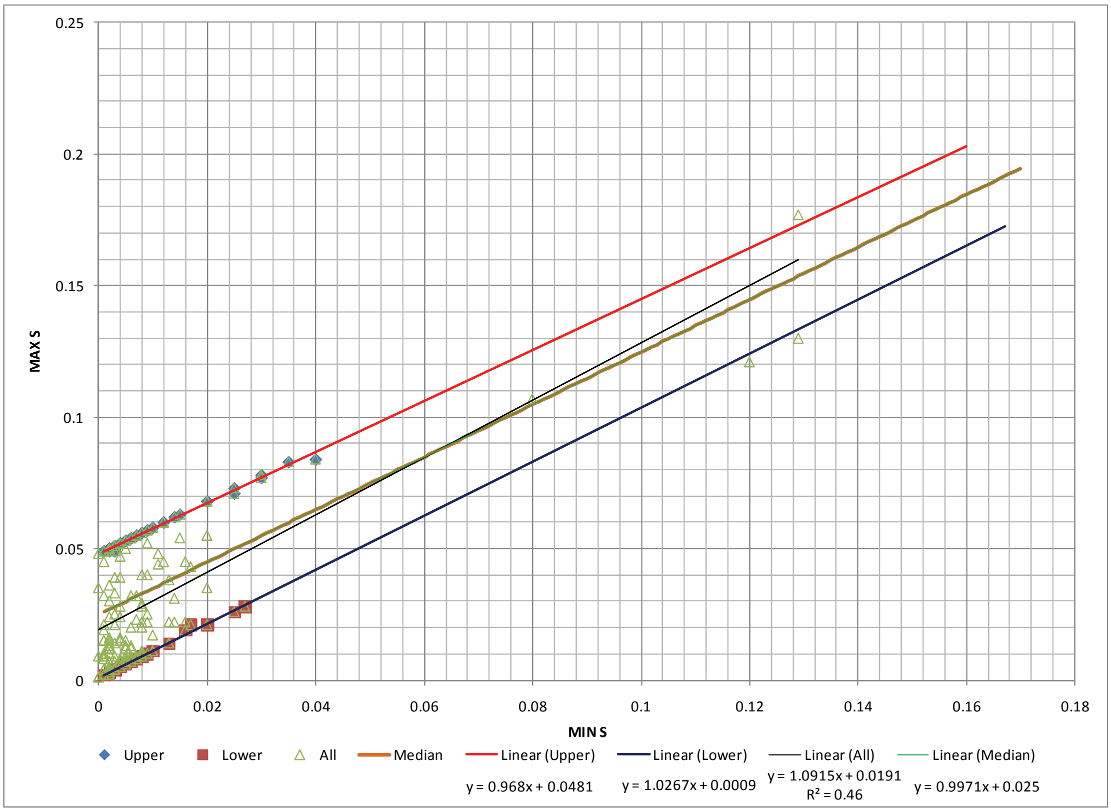


Figure 3.11 Relationship of Minimum Gradient (S_{MIN}) and Maximum Gradient (S_{MAX})

Table 3.6 Maximum Gradient Relationships

Series	Relationship	R^2
Regression	$S_{MAX} = 1.0915(S_{MIN}) + 0.0191$	0.46
Upper	$S_{MAX} = 0.9680(S_{MIN}) + 0.0481$	-
Lower	$S_{MAX} = 0.9971(S_{MIN}) + 0.0250$	-

The regression exercise produced linear relationships between S_{MAX} and S_{MIN}. The data were found to be bound between two linear limits. However, the appropriate use of a specific relationship could not be established and the calibrated results were further investigated. It was found that unique geomorphological relationships could be extracted from the data. These relationships were of the linear form obtained in the regression exercise:

$$\boldsymbol{MaxS = Slope \times MinS + Intercept} \qquad 3.3$$

with the upper limit representing geozone A and the lower limit representing geozone F. The other geozones (B, C, D and E) relationships were obtained by following the trends of the 2 limit curves as log-log curves. The slope and intercept values for the maximum slope estimation relationship are tabulated in Table 3.7 and the forms of the relationships are illustrated in Figure 3.12. Geozones are based upon the valley slope (i.e. S_{MIN}), therefore the maximum gradient estimation equations are limited to the appropriate gradient ranges for the zones and these ranges are tabulated in Table 3.7.

Table 3.7 Parameters of the Maximum Gradient Estimation Equation and Valley Slope Ranges for Geozones*

GEOZONE	A	B	C	D	E	F
INTERCEPT	0.05	0.04	0.03	0.02	0.003	0.0001
SLOPE	0.96	0.97	0.99	1.0	1.1	1.2
SLOPE RANGE	>0.1	**0.04-0.99**	0.02-0.039	0.005-0.019	0.001-0.005	0.0001-0.001

*After Rowntree and Wadeson (1999)

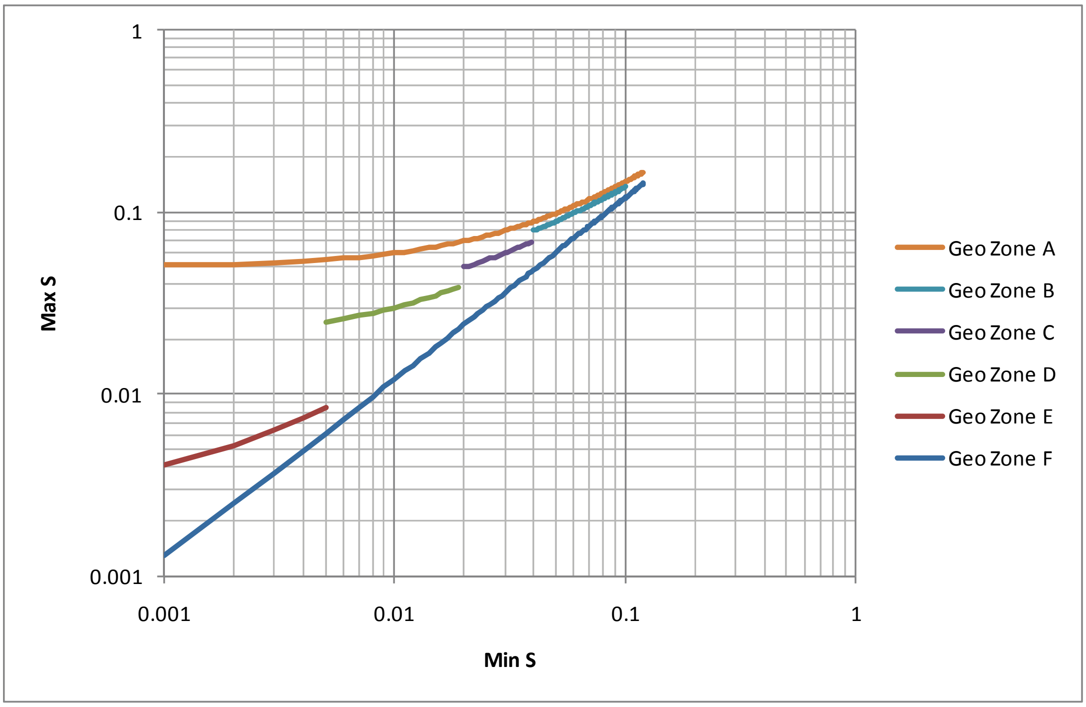


Figure 3.12 Relationship of maximum gradient and minimum gradient per geozone

3.4.6 Macro Roughness Relationships

Macro roughness represents the divergence of the channel form away from the basic channel shape. It represents the large roughness elements that make up the cross section, typically large boulders, outcrops or other variations in the cross-section. In the calibration programme, macro roughness is modelled as perturbations of the basic channel shape and involves using a random number generator. Figures 3.13 and 3.14 illustrate the relationship between macro roughness and y_{MAX} and W_{MAX} respectively. Substantial scatter is observed in both series, with power relations producing moderate correlations. The power relations and R^2 values are tabulated in Table 3.8.

Table 3.8 Macro Roughness Relationships

Series	Relationship	R^2
Macro vs. y_{MAX}	$Macro = 0.3279(y_{MAX})^{0.9743}$	0.42
Macro vs. W_{MAX}	$Macro = 0.0914(W_{MAX})^{0.554}$	0.39

The scatter observed in these series may be attributed to a source of 'operator' error. During the calibration exercise, the aim was to achieve a good fit to the observed cross-sectional area – depth relationship. In order to achieve this, the macro roughness would be increased, significantly at times, for cross-sections containing a step in the bank or terraces, thus deviating from the correct definition of what macro roughness should represent. The result is a relatively frequent over-estimate of macro roughness. Two examples of this are illustrated in Figure 3.15. Both examples have good fits to the observed cross-sectional area-depth relationship and the estimated shape is acceptable compared to the observed shape. However, to achieve the fit, the macro roughness is over-estimated.

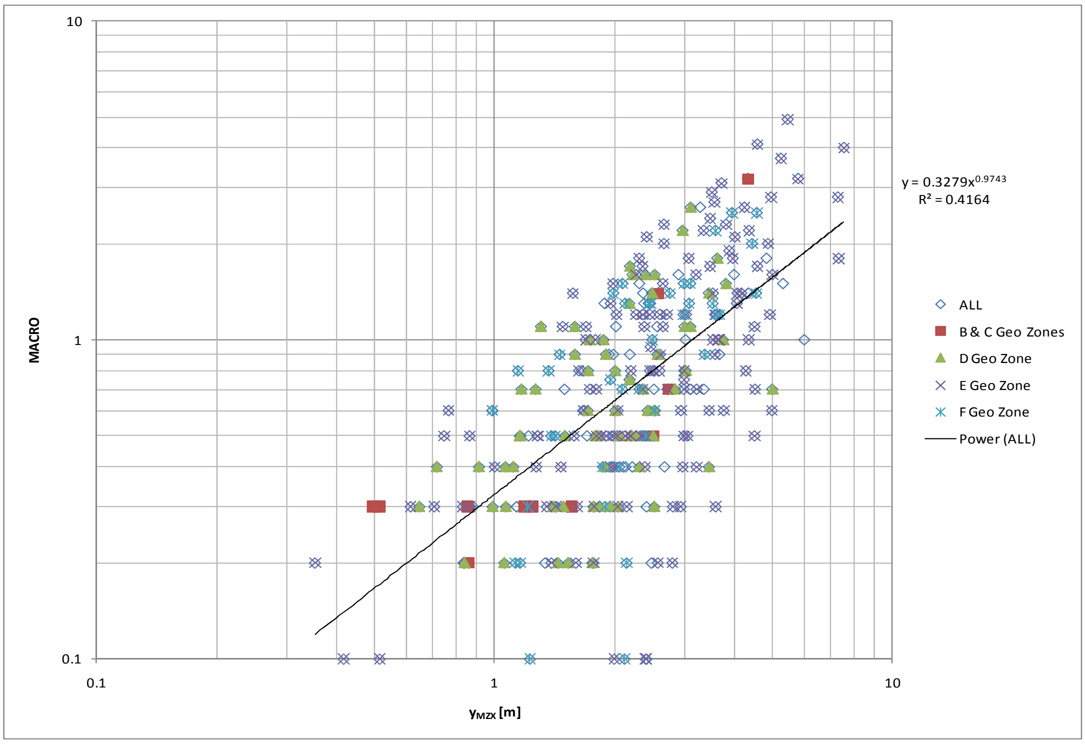


Figure 3.13 Relationship between Macro Roughness and Maximum Flow Depth (y_{MAX})

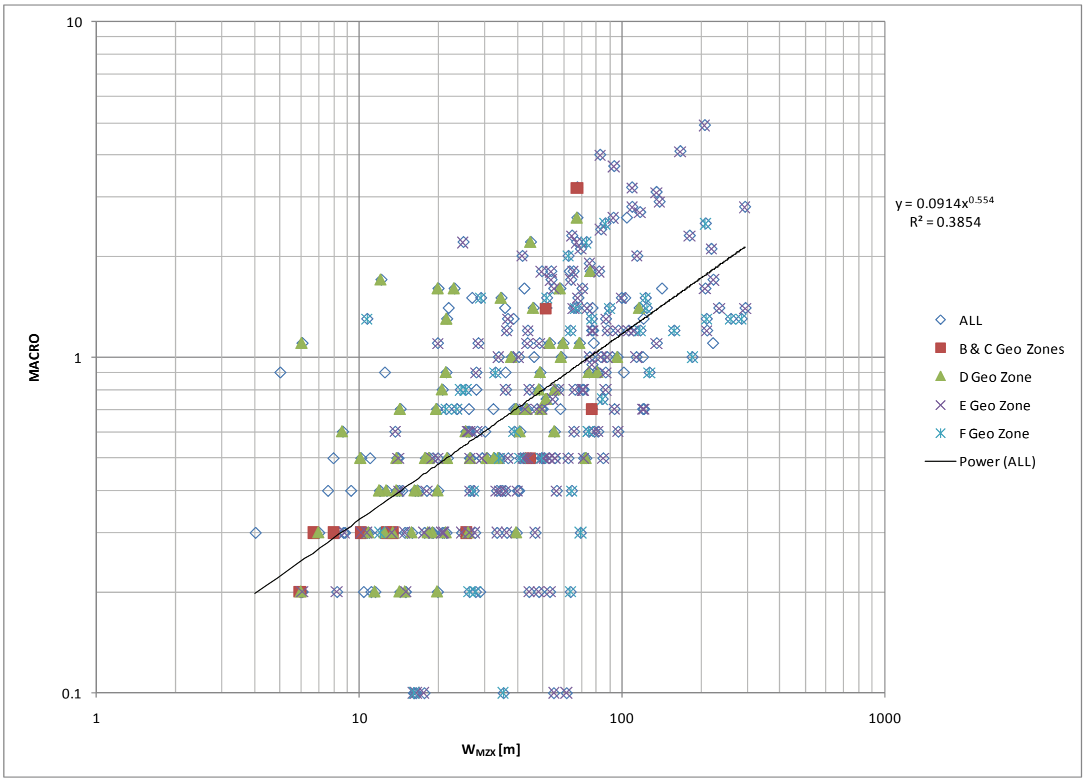
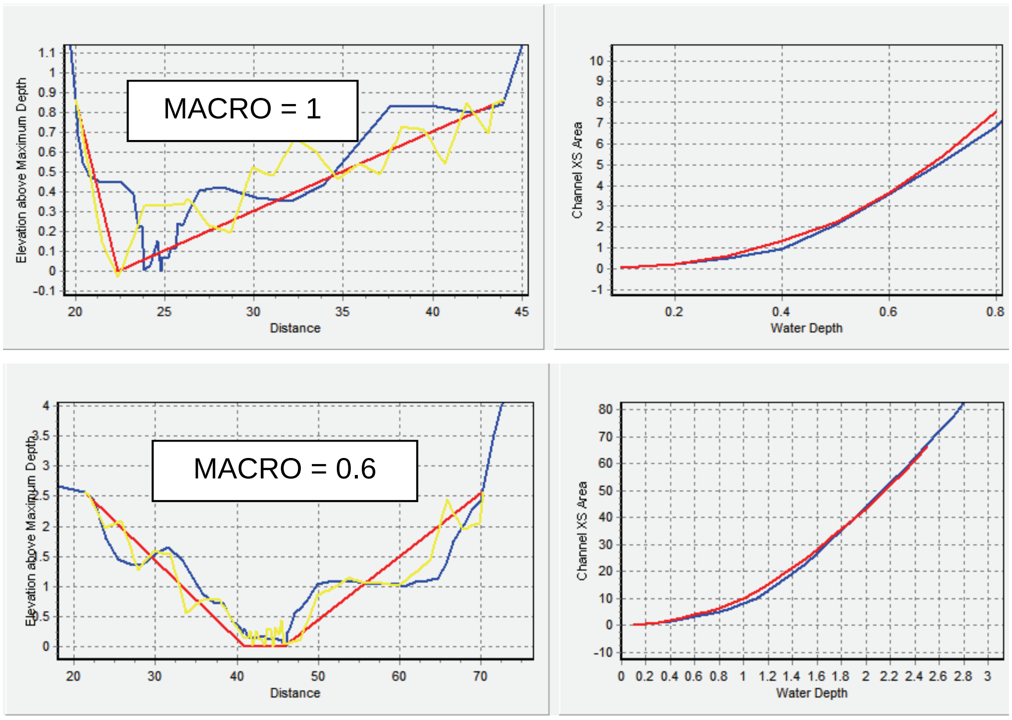


Figure 3.14 Relationship between Macro Roughness and Maximum Flow Depth (WMAX)



Note: For the X-section graphs the blue lines are the surveyed channel, the red lines the basic shape and the yellow lines the simulated X-section. For the depth-area graphs the blue lines are observed and the red simulated.

Figure 3.15 Example of Macro Roughness Over-Estimated

Moderately correlated power relationships were achieved for relationships of Macro Roughness with y_{MAX} and W_{MAX}. Examining these relationships further indicated that power relations for each geozone were possible.

Power relationships of $\frac{W_{MAX}}{y_{MAX}}\ vs\ \frac{Macro}{y_{MAX}}$ for each geozone were developed as:

$$\frac{Macro}{Y_{max}} = Const \times \frac{W_{max}}{Y_{max}}^{Power} \qquad 3.4$$

The values for the 'Const' and 'Power' are tabulated in Table 3.9 and the form of the relationships illustrated in Figure 3.16. The relationships were obtained through inspection assuming that the calibrated high macro roughness values are over-estimates because of the reasons discussed above (i.e. equifinality of complex models and/or 'operator' errors). It is noted that the relationship for geozone D was developed based on the trends of the other geozone relationships as the calibrated results for geozone D did not follow the incremental step trend observed with the other geozone relationships.

Table 3.9 Parameters of the Macro Roughness Estimation Equation

GEOZONE	A	B	C	D	E	F
CONST	0.15	0.12	0.09	0.07	0.06	0.05
POWER	0.50	0.50	0.50	0.50	0.50	0.50

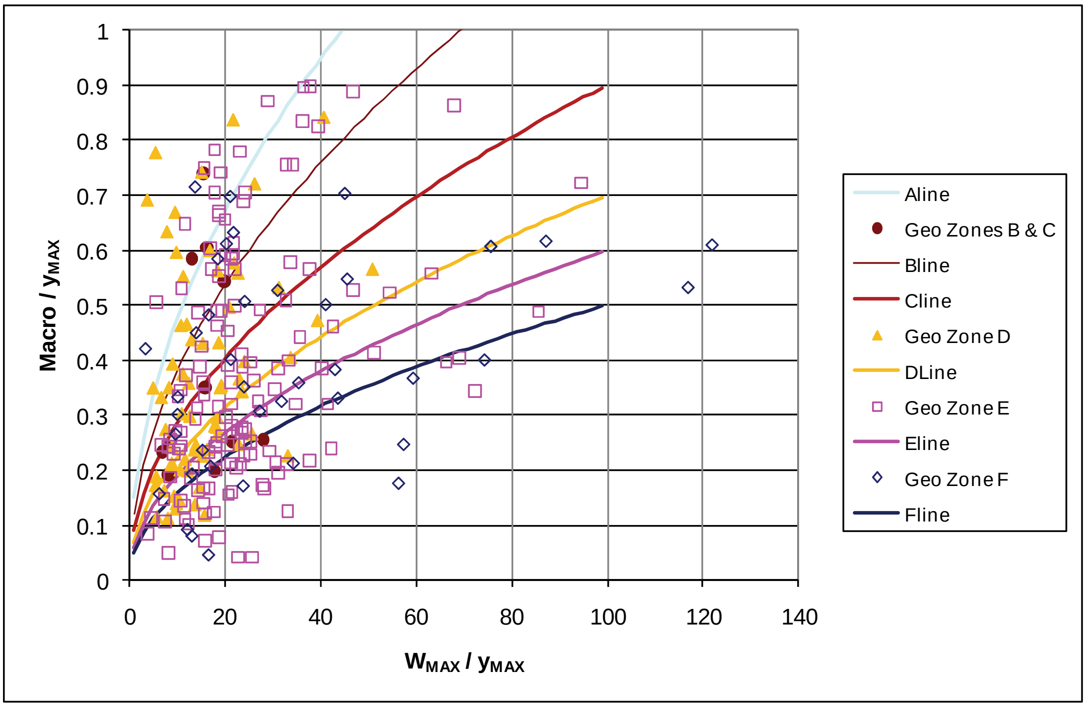


Figure 3.16 Relationships for the Estimation of Macro Roughness

3.4.7 Micro roughness relationship

Micro roughness represents the size of the mobile sediment part of the channel cross-section and applies to the bed width part of the cross-section. The roughness elements represented are typically cobbles, coarse and fine sediments. Attempts to obtain relationships of micro roughness to combinations or ratios of; macro roughness, valley slope, W_{MAX}, Y_{MAX}, Shape, Geozone produced very weak correlations (R^2: 0.15 – 0.25). In the conceptual approach, it was decided to estimate micro roughness using sediment transport theory. The Shields diagram, and therefore the van Rijn's (1984) Shields relationship, and the Hjulström curve are basically similar (Richards, 1982) and it was decided to proceed with the use of the Hjulström curve noting that the Hjulström or Shields curves are difficult to apply to natural rivers, where grain size heterogeneity, variable grain exposure and instantaneous velocity variations render incipient motion a probabilistic phenomenon (Yalin, 1977). However, it is assumed to be adequate for a desktop model application.

According to the Hjulström diagram, there is a relationship between sediment size the average cross-sectional velocity at a flow depth of 1 m. Distinct boundaries occur at the point of entrainment and deposition. The micro roughness size is assumed to be the sediment size that will begin to entrain and therefore the entrainment curve was used as the micro roughness estimation relationship, with the following relationships obtained from the Hjulström diagram:

$$\boldsymbol{Vel_{1m} = 1.3D^2 + 9D + 14.5}$$
$$\boldsymbol{14.5 < Vel_{1m} < 70} \qquad 3.5$$

$$\boldsymbol{Vel_{1m} = 85.1\, lnD - 59.36} \qquad \boldsymbol{Vel_{1m} \geq 70} \qquad 3.6$$

where $\mathbf{Vel_{1m}}$ is the average cross-sectional velocity at a flow depth of 1 m, D is the sediment size in mm.

By definition, the micro roughness cannot equal or exceed the macro roughness, to prevent this from occurring, the micro roughness is limited to 80% of the macro roughness. The choice of 80% is somewhat arbitrary but tests of the estimation equation for a variety of different conditions suggested that this limitation will be rarely required (i.e. micro roughness is generally a lot less than macro roughness).

3.4.8 Manning n (n_{MIN} and n_{MAX}) relationships

Manning n (n_{MIN} and n_{MAX}) values are the coefficients representing the resistance of the channel and are used in the Manning equation for the determination of velocity/discharge and hence the rating curve (i.e. flow depth vs. discharge), with n_{MIN} representing the roughness coefficient during high flow conditions (i.e. y_{MAX}) and n_{MAX} representing the roughness coefficient during low flow conditions. Several regression analyses were attempted to obtain relationships for these parameters with physical variables or other parameters but weak correlations (R^2: 0.15 – 0.25) were achieved. The conceptual approach approximated the following relationships:

$$\boldsymbol{n_{Min} = n_{Base} + 0.025 * Macro/Y_{Max}} \qquad 3.7$$

3.7

$$\boldsymbol{n_{Max} = Micro^{0.7} + 0.2 \times Macro} \qquad 3.8$$

Where:

n_{Base} is the nominal Manning n used in the maximum depth calculation and varies with geozone.

y_{MAX} is the Maximum Flow Depth (m).

$Macro$ is the Macro roughness (m).

$Micro$ is the Micro roughness (m).

The n_{MIN} relationship was developed using the assumption that Manning n decreases with increasing flow depth due to the relative submergence of the macro roughness (i.e. the deeper the flow compared to the macro roughness, the less the roughness of the channel). The n_{MAX} relationship was developed using the assumption that at low flows, the resistance is a combination of the macro and micro roughnesses, with the micro roughness having a larger influence on the Manning resistance.

3.4.9 Variability factors

As the flow depth varies with discharge, the Manning n and water surface slope vary with the flow depth. These variations are required to be able to estimate the rating curve when the flow depth varies from 0 to y_{MAX}. The rate of variations are determined as follows:

Manning n Variability: the assumption that Manning n decreases with flow depth and that Manning n is related to the Macro and Micro roughnesses and y_{MAX}, Equation 4.8 was obtained to estimate a value between 5 and 50.

$$\boldsymbol{n_{var} = floor\left(3.5 \times \frac{macro^{-1.5}}{y_{max}} + 0.5\right)} \qquad 3.9$$

Slope Variability: determines the variation of slope with water depth in the channel and the following equation was developed and applied to an S-Curve function to estimate a value between 5 and approximately 50.

$$\boldsymbol{S_{VAR} = Integer\left\{\left(1.25 + 3.75 \times {}^{S_{MAX}}/_{S_{MIN}}\right) + 0.5\right\}} \qquad 3.10$$

The variability of 5 represents a low variability (i.e. not much change in the n_{MAX} or S_{MAX} values until flow depth is close to y_{MAX}) and 50 represents a high variability (i.e. sudden change in n_{MAX} or S_{MAX} values to n_{MIN} or S_{MIN} at low flow depth)

3.5 VALIDATION AND REFINEMENT OF THE ESTIMATION APPROACHES

The hydraulic sub-model parameter relationships developed in the conceptual approach were tested for their validity by comparing the results obtained against the past EWR hydraulic data and was achieved by using an updated calibration program. The calibration program was updated with the parameter relationships discussed in Section 3.4 and required the following inputs:

- Observed XS Profile (Elevation vs. Chainage).
- Observed Rating Curve (Depth vs. Flow).
- Geozones (1-6) – where 1 = Geozone A and 6 = Geozone F.
- Flood Region (1-13) – 13 flood regions of South Africa from Mkhandi and Kachroo (1997).
- Hydrological Variability – hydrological variability index as calculated in the Desktop Reserve (Hughes and Hannart, 2003).
- Valley Gradient (m/m).
- Catchment Area (km^2).
- Constant (a) – coefficient for $W_{MAX} = aQ_c{}^b$.
- Exponent (b) – coefficient for $W_{MAX} = aQ_c{}^b$.

Hydrological variability was a new input parameter required for the validation exercise and the data had to be obtained for the past EWR sites. However, hydrological variability was obtainable for only 82 sites on the hydraulic database representing geozones D,E and F with catchment areas ranging from 20 km^2 to 50 000 km^2 and located in 7 flood regions. The revised calibration program produced the following outputs, which were used to generate a cross-sectional profile and rating curve:

- Mean Annual Flood ($\bar{Q}$).
- Channel Forming Discharge (Q_C).
- Maximum Channel Width.
- Channel Bed Width %.
- Minimum Gradient (SMIN) – equal to Valley Gradient.
- Maximum Gradient (SMAX).
- Gradient Variability.
- Nominal Manning n value.
- Macro Roughness.
- Micro Roughness.
- Minimum Manning n.
- Maximum Manning n.
- Manning Variability.

The validity of the parameters were then assessed by comparing the observed XS profile and rating curve against the estimated XS profile and rating curve, using the coefficient of efficiency to establish the accuracy between the estimated and observed XS profile and rating curve. In cases where the XS profile generated was not a good fit to the observed profile, the values for the coefficients in the maximum channel width estimation equation were changed until a good fit was achieved and where the rating curve was not a good fit, the n_{MIN}, n_{MAX} and S_{MAX} parameters where changed along with the variability coefficients to obtain a good fit, i.e. it was assumed that S_{MIN} was correctly estimated.

The estimated parameter relationships were found to produce channel geometry and rating curve characteristics similar to the observed data with certain parameter relationships requiring refinements to estimate the hydraulic characteristics more accurately. Discussions of the calibrated coefficients of W_{MAX} and the refinement of the hydraulic parameters (% Bed Width, y_{MAX}, Macro Roughness, n_{MIN} and n_{MAX}) are provided below.

3.5.1 W_{MAX} Coefficients – constant (a) and exponent (b)

The coefficients (a and b) of the width estimation equation, $W_{MAX} = aQ_c{}^b$, were adjusted until the estimated maximum width represented a good fit when compared to the observed XS. An ascending trend, relative to Geozones D, E and F, was observed for coefficient b and coefficient a remained constant. The trend was extrapolated to produce coefficients for Geozones A, B and C as there was insufficient information to obtain these values. The coefficients are listed in Table 3.10 related to the geozone.

Table 3.10 Values of Coefficient a and b for WMAX

GEOZONE	A	B	C	D	E	F
Coefficient a	1.35	1.35	1.35	1.35	1.35	1.35
Coefficient b	0.45	0.55	0.65	0.65	0.75	0.75

Hydrological variability indices of several more sites were determined after the refined hydraulic relationships were set and these sites were then used as further testing of the relationships. It was found that the maximum width was being over-estimated for geozones

E and F (see Figure 3.17). From Figure 3.17 it can be clearly seen that the width is being significantly over-estimated.

A two-stage relationship was developed to estimate the maximum width for Geozones E and F; no change in the coefficients for catchment areas less than 250 km^2 and additional coefficients were calibrated for catchment areas greater than 250 km^2. The revised coefficients are tabulated in Table 3.11 and illustrated in Figure 3.18, it is noted that coefficients for Geozones C and D were further refined during this exercise.

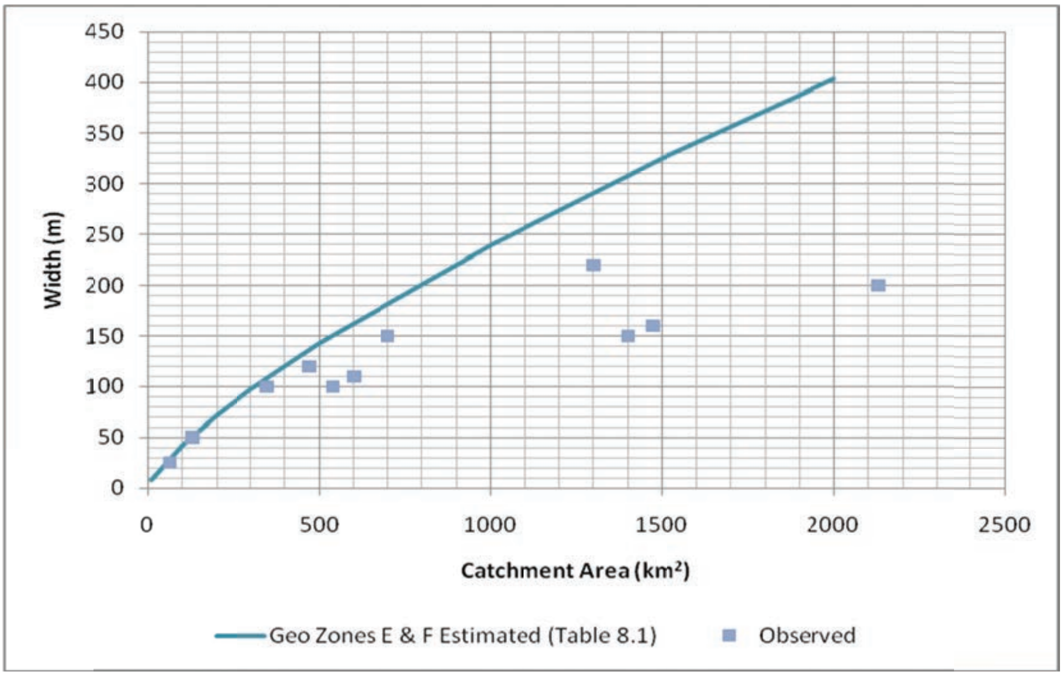


Figure 3.17 Estimated and Observed Maximum Width for Geozones E and F

Table 3.10 Revised Values of Coefficient a and b for WMAX

GEOZONE	A	B	C	D	E and F	E and F
CATHMENT AREA (km^2)	**All**	**All**	**All**	**All**	**<250**	**>250**
Coefficient a	1.35	1.35	2.22	2.22	1.35	4.95
Coefficient b	0.45	0.55	0.55	0.55	0.75	0.50

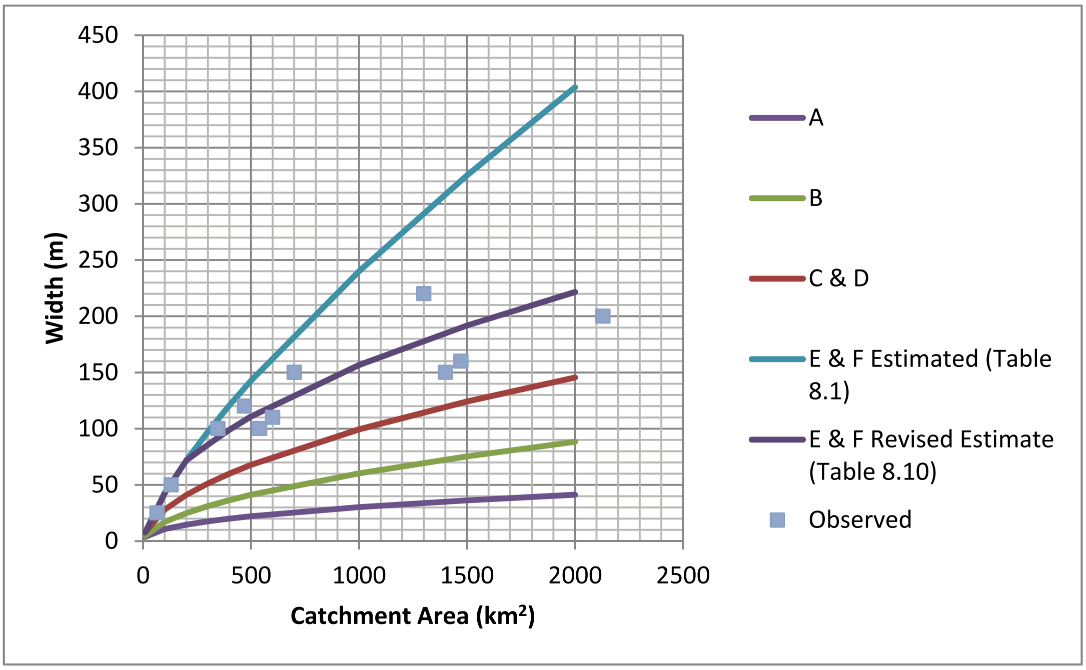


Figure 3.18 Revised Maximum Width Estimate for Geozones E and F

3.5.2 Refinement of % bed width estimation

Through visual observations, it was noticed that the % bed widths was underestimated for Geozones C, D and E and were subsequently increased to 25%, 40% and 60% respectively.

3.5.3 Maximum depth

The y_{MAX} determined using the Manning equation for the simple trapezoid channel with no macro roughness, a nominal Manning n and W_{MAX} was underestimated. This was noticed when macro roughness was added to the channel cross-section and the channel forming discharge (Q_c) could not be accommodated within the estimated channel geometry because the cross sectional area was reduced and the wetted perimeter increased, resulting in less discharge for the given set width and depth. The effects of the estimated macro roughness elements were therefore included in the iterative calculation for y_{MAX}, resulting in deeper channels that could accommodate Q_C.

3.5.4 Macro roughness

It was noticed that half the macro roughness value that was calculated was being plotted on the estimated XS profile, thus affecting the cross-sectional area vs. depth relationships and the rating curve. Adjustments to the plotting procedure of the estimated XS profile was done in order to plot the macro roughness calculated. This adjustment created an additional plotting error; the XS profile was always 'very rough' and this was not expected for foothill and lowland rivers (i.e. Geozone F). Conceptually, it was expected that the mountain (headwater) streams (Geozone A) would produce 'rough' sections due to the high valley gradients, narrow channels and bed material types located in the areas (i.e. predominantly bedrock and boulders) and that the lowland rivers (Geozone F) would be much 'smoother' due to the low valley gradients, wide channel and high sediment. In order to achieve the effect of ‘very rough’ channels in mountain streams down to ‘smooth’ channel in lowland rivers, the ratio of macro roughness to y_{MAX} was limited according to the Geozone (Table 3.12), i.e. if the right hand side of equation 3.4 was determined to be greater than the fractions in Table 3.12, the ratio of macro roughness to y_{MAX} would be set equal to the respective fraction in Table 3.12. It was noted that the limits was applied to the overall macro roughness value and the effect on the other relationships dependent on macro roughness (viz. n_{MIN} and n_{MAX}) was considered in their refinement.

Table 3.11 Maximum Ratio of Macro to yMAX per Geozone

GEOZONE	A	B	C	D	E	F
Maximum Macro to y_{MAX} Ratio	0.8	0.6	0.5	0.4	0.3	0.2

3.5.5 Manning n values

The n_{MIN} and n_{MAX} obtained from equations 3.7 and 3.8 respectively were plotted against the minimum and maximum Manning n coefficients modelled in the past EWR studies (Figures 3.19 and 3.20). The plots indicated that n_{MIN} was being under-estimated and n_{MAX} was being over-estimated. An alternate relationship for n_{MIN} was developed (Equation 3.11) which produced better estimates when compared with the past EWR minimum roughness coefficients. The constants in the n_{MAX} relationship (Equation 3.8) were adjusted to lower the estimated values in order to achieve better correlations with the maximum roughness coefficients used in the past EWR studies (Equation 3.12).

$$\boldsymbol{n_{Min}} = \boldsymbol{ConstN} \times \left(\frac{\boldsymbol{W_{Max}}}{\boldsymbol{Y_{Max}}}\right)^{\boldsymbol{PowerN}} \qquad 3.11$$

Where ConstN and PowerN are constants dependent upon the geozone (Table 3.13)

Table 3.13 Parameters of the Minimum Manning Estimation Equation 3.11

GEOZONE	A	B	C	D	E	F
CONSTN	0.050	0.040	0.035	0.035	0.020	0.020
POWERN	0.250	0.250	0.250	0.250	0.250	0.250

$$\boldsymbol{n_{Max}} = \mathbf{0.4} \times \boldsymbol{Micro}^{\mathbf{0.5}} + \mathbf{0.1} \times \boldsymbol{Macro} \qquad 3.12$$

It is evident from the publications of Manning roughness coefficients that maximum and minimum Manning n values are rarely equal or similar and it was decided to include a limit to the smallest value that n_{MAX} could be set at, if n_{MAX} was calculated to be less the 1.2 times n_{MIN}, then n_{MAX} would be set to $1.2n_{MIN}$ and therefore allowing for Manning n to vary with flow depth.

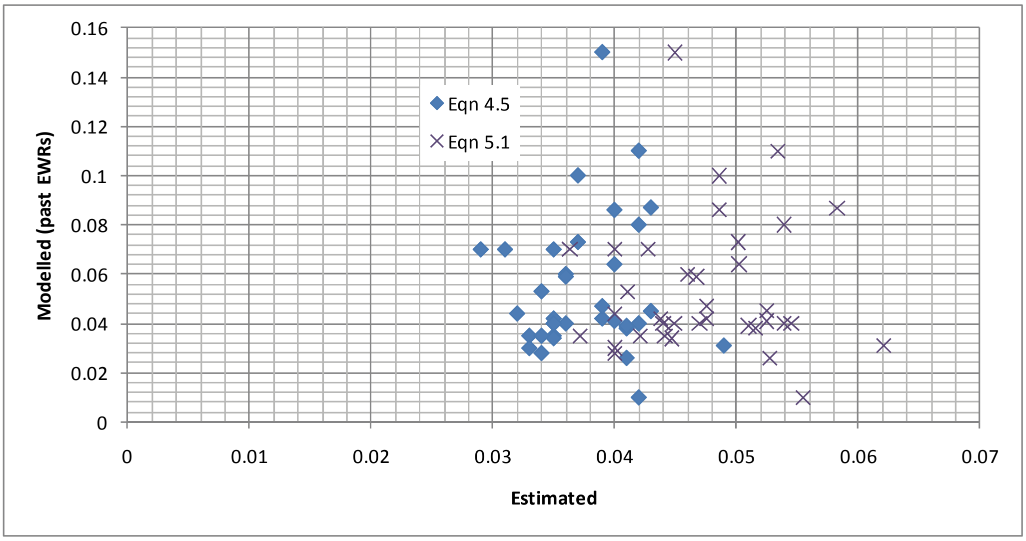


Figure 3.19 n_{MIN} **– Estimated vs. Modelled**

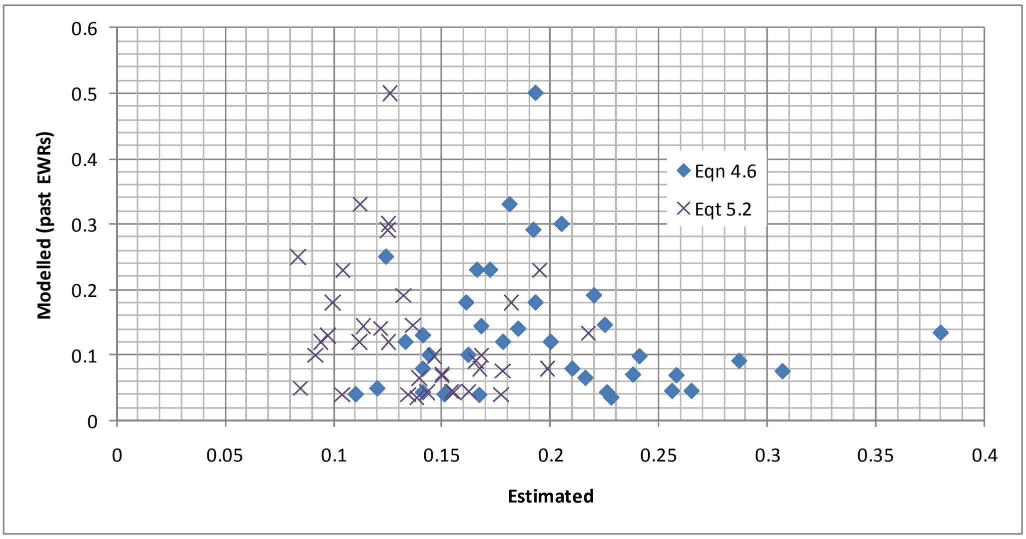


Figure 3.20 n_{MAX} **– Estimated vs. Modelled**

The minimum Manning estimation relationship (Equation 3.11) was further compared to other published roughness coefficients viz. Barnes (1967), Anable (1996), Hicks and Mason (1998) and Wohl and Wilcox (2005). Bankfull depth, bankfull width and valley slope were obtained from Barnes (1967), Anable (1996) and Wohl and Wilcox (2005). Hicks and Mason (1998) did not provide bankfull hydraulic characteristics but did include the mean annual flood for each site and it was assumed that the mean annual flood would produce a bankfull condition at each site. Hicks and Mason (1998) also did not give depth and width information and so the depths were approximated to equal the hydraulic radius and the width was computed as being approximately equal to the ratio of cross sectional flow area to hydraulic radius. The hydraulic geometry relationships were determined for each site and then the mean annual flood was used to determine the bankfull width and bankfull depth. The valley slope was approximated to equal to frictional slope, as no valley slope information was available, and was interpolated for the mean annual flow value.

A plot of the estimated n_{MIN} and published bankfull Manning coefficient is illustrated in Figure 3.21. The overall result of the comparison is that Equation 3.11 over-estimates the minimum Manning roughness coefficient for bankfull conditions. The reasons for the over-estimates may be attributed to: (i) different bankfull definitions compared to this study, (ii) the variations in bed and vegetation composition has been explicitly taken into account in the published literature but implicitly in this study, (iii) the geozone based on valley slope may not be applicable in those countries and/or (iv) differences in hydrology or hydrological regimes between the countries.

As discussed, the interrelationship of the parameters involved in determining open channel hydraulics is complex and the same result may be achieved through various combinations of the parameters developed and so the assessment of the accuracy of each parameter may be misleading and it was decided that each parameter has been calibrated to an acceptable level of uncertainty for a desktop application. The assessment of overall output of the hydraulic sub-model (i.e. hydraulic flow-depth classes), which is passed onto the ecological sub-model, would be a better indication of the accuracy of the estimated desktop hydraulic conditions.

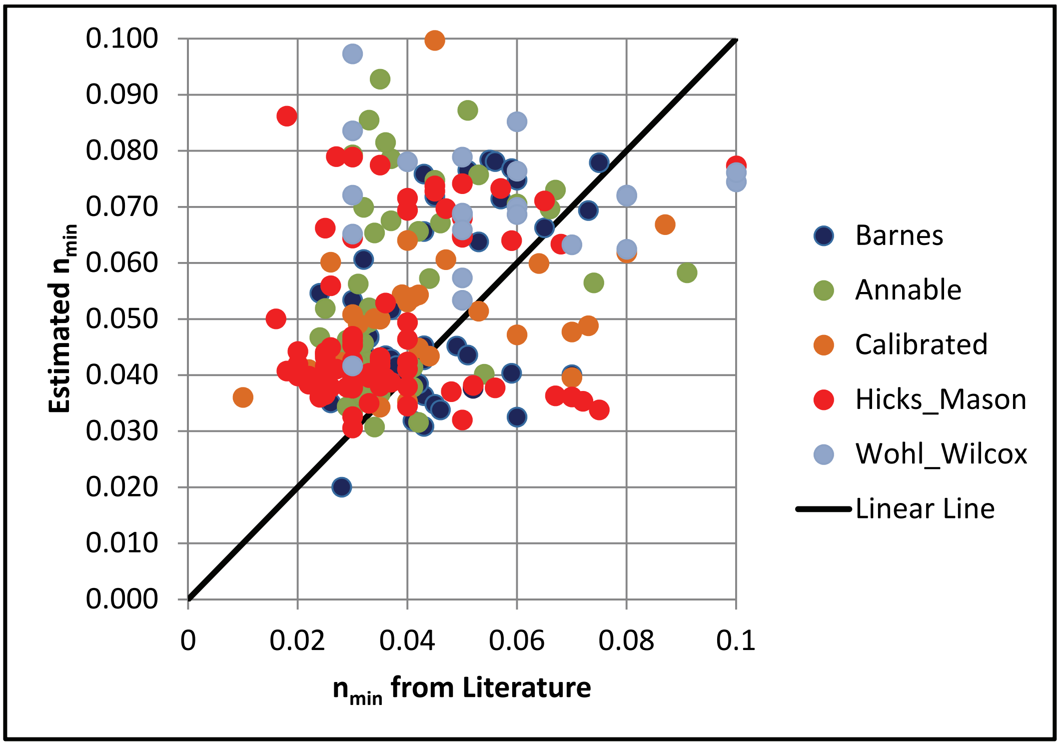


Figure 3.21 Comparison of Published Bankfull n_{MIN} and Estimated n_{MIN} using the Published Hydraulic Conditions

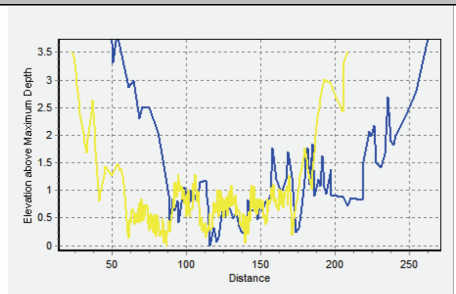
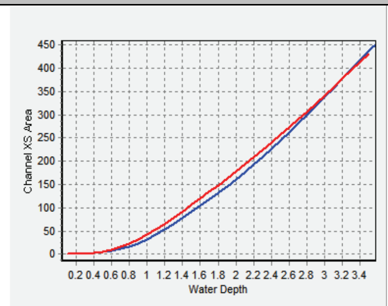
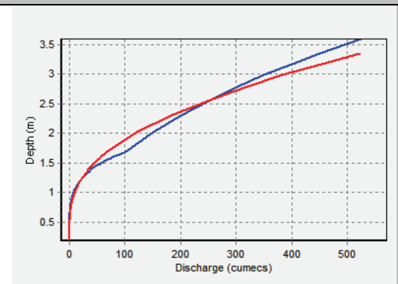
The calibration programme was updated with the refined estimation relationships (Table 3.14) and the revised estimated XS profile and rating curves were compared to the observed data. The resulting estimated XS profiles and rating curves were found to be improved estimates and several screenshots are provided in Figure 3.22 to illustrate the accuracy with which the channel geometry and hydraulic characteristics (i.e. rating curve) have been reproduced. The hydraulic sub-model of the prototype version of the Revised Desktop

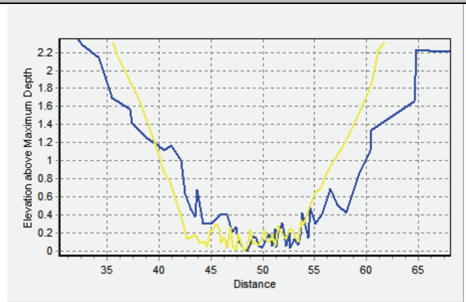
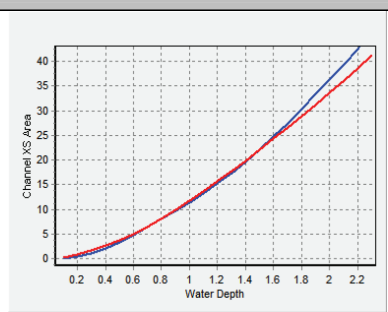
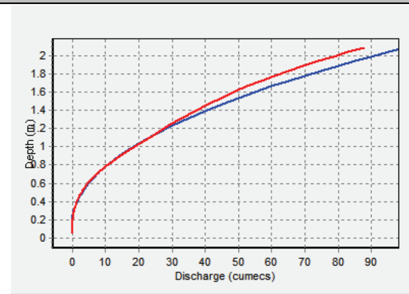
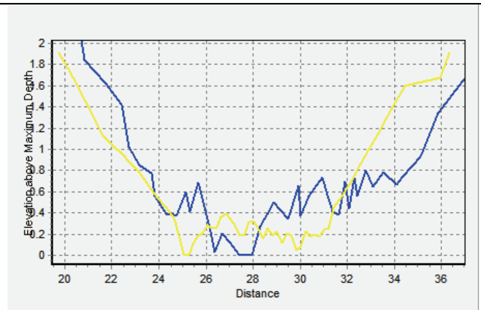
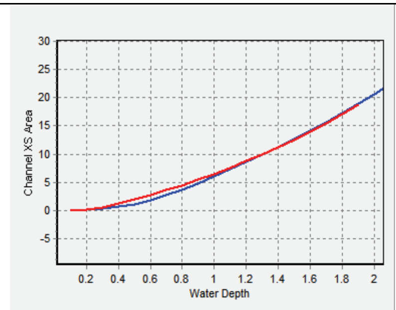
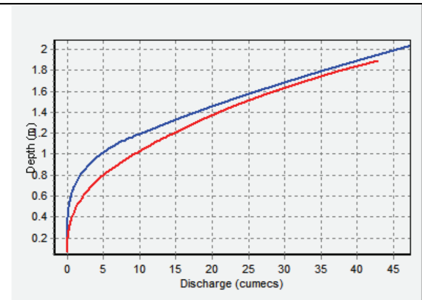
Reserve Model was updated with the refined estimation relationships tabulated in Table 3.14 and past EWR sites locations were used to generate desktop hydraulic conditions. The results of some of these tests are discussed in the following section of the report (Section 3.6)

Table 3.14 Final Estimation Relationships Incorporated into the Hydraulic Sub-Model

PARAMETER	RELATIONSHIP	EQN NO.	COEFFICIENTS or CONSTANTS (per Geozone)						
				A	**B**	**C**	**D**	**E**	**F**
Maximum Channel Width (W_{MAX})	$W_{MAX} = aQ_c{}^b$	3.2	**a**	1.35	1.35	2.22	2.22	1.35 or 4.95	1.35 or 4.95
			b	0.45	0.55	0.55	0.55	0.75 or 0.5	0.75 or 0.5
% Bed Width				10	10	25	40	60	80
Minimum Gradient	Equal to Valley Slope								
Maximum Flow Depth (Y_{MAX})	Use of Manning Equation – solved iteratively								
Maximum Gradient (S_{MAX})	$MaxS = Slope \times MinS + Intercept$	3.3	**INTERCEPT**	0.05	0.04	0.03	0.02	0.003	0.0001
			SLOPE	0.96	0.97	0.99	1.0	1.1	1.2
			GRADIENT RANGE	>0.1	0.04–0.99	0.02-0.039	0.005-0.019	0.001-0.005	0.0001-0.001
Macro Roughness	$\frac{Macro}{Y_{max}} = Const \times \frac{W_{max}}{Y_{max}}^{Power}$	3.4	**CONST**	0.15	0.12	0.09	0.07	0.06	0.05
			POWER	0.50	0.50	0.50	0.50	0.50	0.50
			Limitation of $\frac{Macro}{Y_{max}}$	0.8	0.6	0.5	0.4	0.3	0.2
Micro Roughness	$Vel_{1m} = 1.3D^2 + 9D + 14.5$ for $14.5 < Vel_{1m} < 70$	3.5							
	$Vel_{1m} = 85.1\, lnD - 59.36$ for $Vel_{1m} \geq 70$	3.6							
Minimum Manning n (n_{MIN})	$n_{Min} = ConstN \times \left(\frac{W_{Max}}{Y_{Max}}\right)^{PowerN}$	3.11	**CONSTN**	0.050	0.040	0.035	0.035	0.020	0.020
			POWERN	0.250	0.250	0.250	0.250	0.250	0.250
Maximum Manning n (n_{MAX})	$n_{Max} = 0.4 \times Micro^{0.5} + 0.1 \times Macro$	3.12							

PARAMETER	RELATIONSHIP	EQN NO.	COEFFICIENTS or CONSTANTS (per Geozone)						
				A	B	C	D	E	F
Manning n Variability	$n_{var} = floor\left(3.5 \times \frac{macro^{-1.5}}{y_{max}} + 0.5\right)$	3.9							
Gradient Variability	$S_{VAR} = Integer\left\{\left(1.25 + 3.75 \times {S_{MAX}}/{S_{MIN}}\right) + 0.5\right\}$	3.10							

SITE NAME	CROSS-SECTIONAL PROFILE - Observed Profile - Estimated Profile	CHANNEL XS AREA VS WATER DEPTH - Observed - Estimated	RATING CURVE - Observed - Estimated
Crocodile 6			

SITE NAME	CROSS-SECTIONAL PROFILE - Observed Profile - Estimated Profile	CHANNEL XS AREA VS WATER DEPTH - Observed - Estimated	RATING CURVE - Observed - Estimated
Kromme 2			
Sabie_Sand 1			

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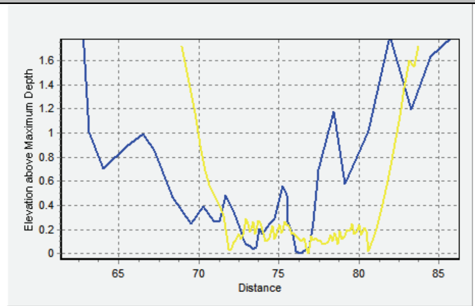
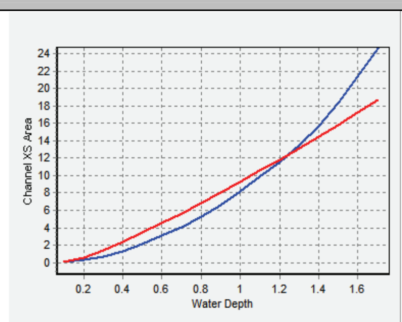
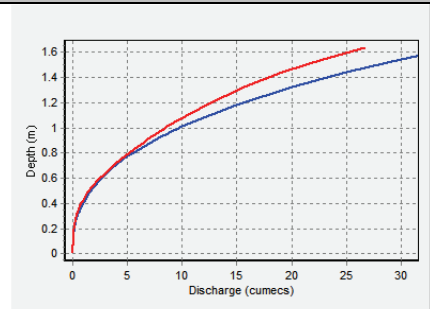
- Observed Profile
- Estimated Profile</th><th>CHANNEL XS AREA VS WATER DEPTH
- Observed
- Estimated</th><th>RATING CURVE
- Observed
- Estimated</th></tr>
<tr><td>Sabie_Sand 7</td><td>
</td><td>
</td><td>
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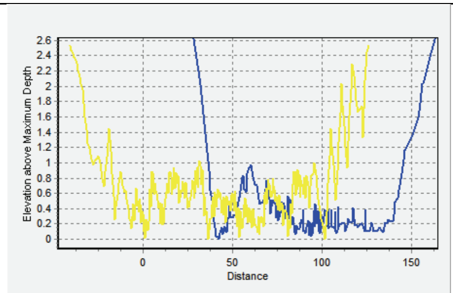
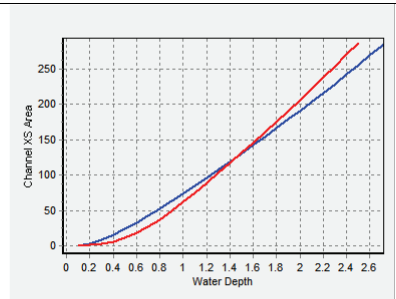
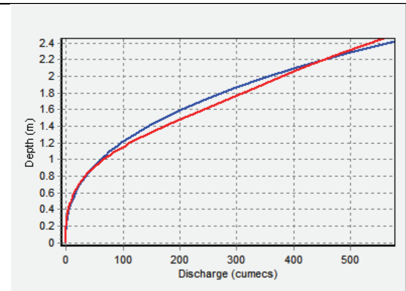
<tr><td>Vaal 4</td><td>
</td><td>
</td><td>
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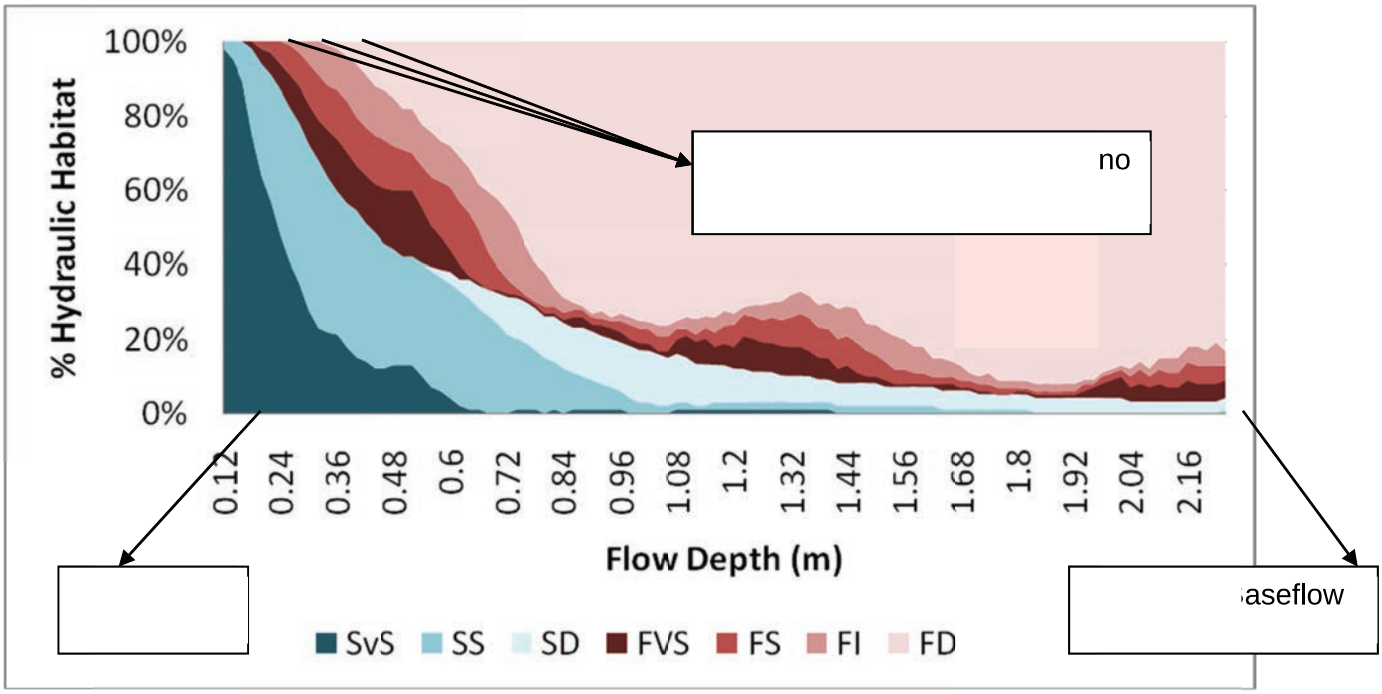
</table>

Figure 3.22 Screenshots of Observed versus Estimated Cross-section Profiles and Rating Curves using the Refined Estimation Relationships

3.6 COMPARISON OF HYDRAULIC HABITAT RESULTS

This section of the report provides some initial comparisons between the hydraulic habitat results obtained for specific Reserve determination sites during the workshops and the results generated from the desktop hydraulic sub-model. The workshop results are based on the surveyed channel cross-sections and calibrated hydraulic parameters, while the model results are based on the channel cross-section characteristics and hydraulic parameters generated using the procedures discussed in the earlier parts of this section of the report. The results are presented and discussed on the basis of different geozones. The desktop hydraulic conditions were modelled using HABFLO (HABitat FLOw Simulation – developed by Hirschowitz et al, 2007) to obtain hydraulic habitat information. The hydraulic habitats are presented as area plots with the horizontal axes representing the depth of flow and the vertical axes the percentage of the channel occupied by the 7 different hydraulic habitats (Figure 3.23).



SvS = Slow, Very Shallow; **SS** = Slow, Shallow; **SD** = Slow, Deep; **FvS** = Fast, Very Shallow; **FS** = Fast, Shallow; **FI** = Fast, Intermediate; **FD** = Fast Deep

Figure 3.23 Example of an Areal Plot of Hydraulic Habitats

In all cases the maximum baseflow discharge was used for the hydraulic analysis because the flow-stress relationship produced by the ecological sub-model specifies a zero stress at the maximum baseflow and a maximum stress of 10 at zero flow. The most important things to note are the frequencies of the fast- deep, intermediate and shallow habitats (FD, FI and FS) as these are the three that are used to determine the stress-flow relationships in the ecology sub-model. It is therefore the rate at which they decline with depth, as well as the depth that these three disappear that is important (Figure 3.23). However, it must also be recognized that there will be differences in the relationships between flow depth and discharge between the workshop and desktop results and these could affect the stress (habitat availability) – flow relationships as well.

The results are presented and discussed on the basis of different geozones (see Figures 3.24 to 3.28). For geozones B and C four sites have been included and the desktop results have been based on setting the geozone according to the information generated at the workshop. It was found that the geozone and valley slope for three of the sites were incompatible and thus two sets of desktop results were generated:

- Assuming the geozone is correct, the valley slope was approximated to equal a slope within the geozone (see blue border area plots below).
- Assuming the valley slope is correct, the geozone was changed to coincide with the valley slope (see red border area plots below)

In all cases the figure titles refer to the Reserve site and the maximum baseflow discharge that was used for the hydraulic analysis. The horizontal axes give the depth of flow while the vertical axes represent the percentage of the channel occupied by the 7 different hydraulic habitats. The most important things to note are the frequencies of the deep, intermediate and shallow fact habitats (FD, FI and FS) as these are the three that are used to determine the stress-flow relationships in the ecology sub-model. It is therefore the rate at which they decline with depth, as well as the depth that these three disappear that is important. However, it must also be recognized that there will be differences in the relationships between flow depth and discharge between the workshop and model (simulated) results and these could affect the stress (habitat availability) – flow relationships as well.

The habitat comparisons presented in this part of the report highlight some of the uncertainties associated with using a desktop approach to defining channel cross-section geometry and hydraulic parameters. The fact that there will be differences in the rating curve shapes between the workshop and simulated results may also compensate for the differences in the habitat – depth relationships. It is difficult to determine the real cause of these differences but is likely to be due to the over-simplification of the cross-sections in the model compared to the observed sites.

Overall, the habitats obtained using the desktop model was found to be acceptable within the accepted ranges of uncertainty. The major differences occur in the distinction between fast deep and fast intermediate habitats. This is not a critical issue with respect to the links with the ecology sub-model, but may be suggestive of some deficiencies in the model cross-sections and hydraulic parameters. One possible problem is that the workshop results tend to suggest that fast habitats disappear at deeper depths while the desktop results suggest that fast habitats are present at very shallow depths.

Some of the results suggest that the model is not very sensitive to the selection of the correct Geo-zone. Changes in the Geo-zone will mainly affect the channel width/depth ratio and it is useful to understand that small changes in this ratio will not affect the habitat relationships.

3.6.1 Geo-Zones B and C

Site E3BLY (Figure 3.24): Desktop results simulate more shallow habitat. The rates of decline are similar in all cases, workshop and desktop.

Site E6SAB (Figure 3.25): Desktop results simulate more fast shallow and no fast deep habitat. The rates of decline are similar with FI and FS habitats being lost at approximately the same rate.

Site E7MOT (Figure 3.26): No fast habitats are observed in workshop and desktop runs. There is a vast difference between the workshop and desktop results in terms of the slow habitats.

Site E9LON (Figure 3.27) Desktop results simulate more fast habitats and the fast habitats are lost at lower depths.

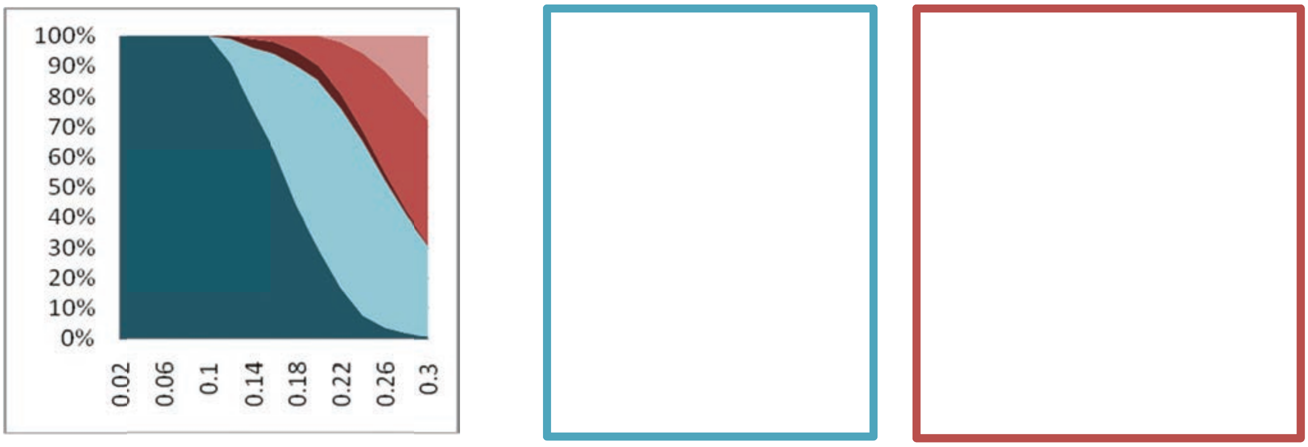


Figure 3.24 Site E3BLY

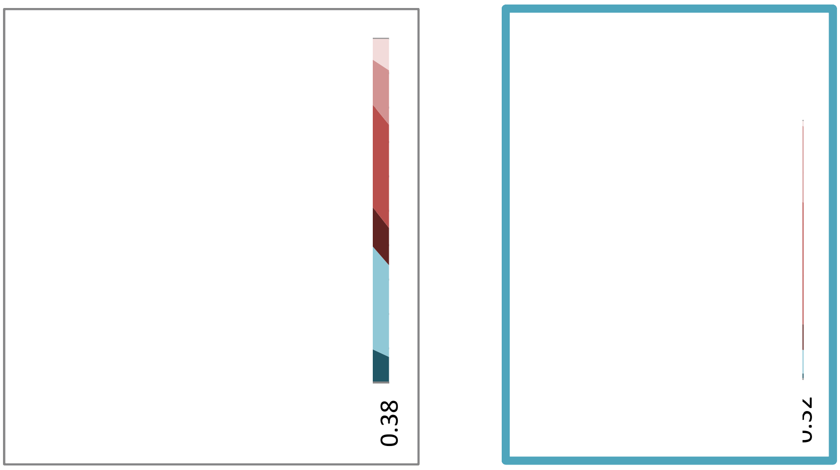


Figure 3.25 Site E6SAB

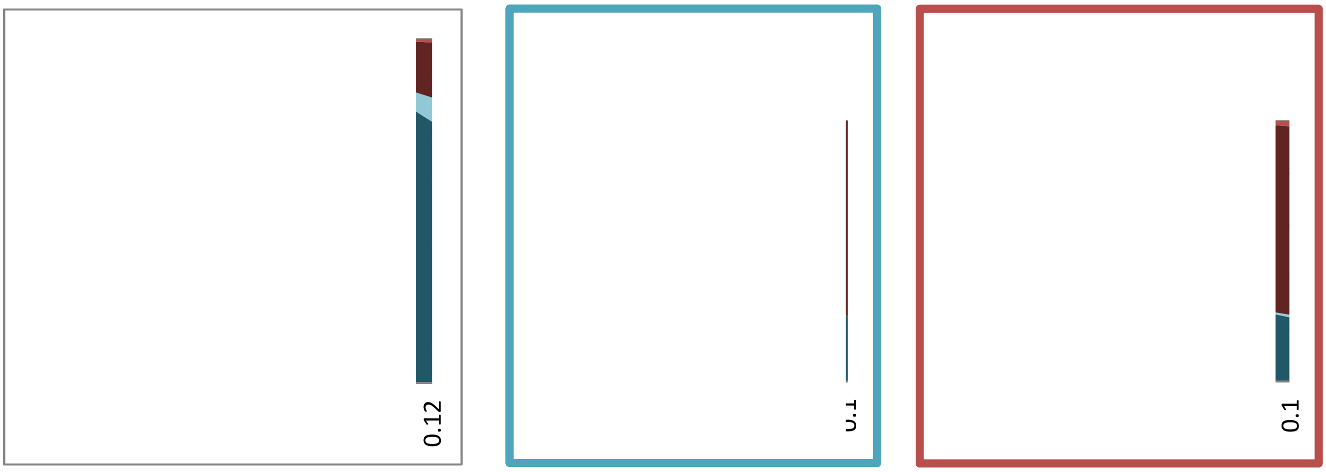


Figure 3.26 Site E3BLY

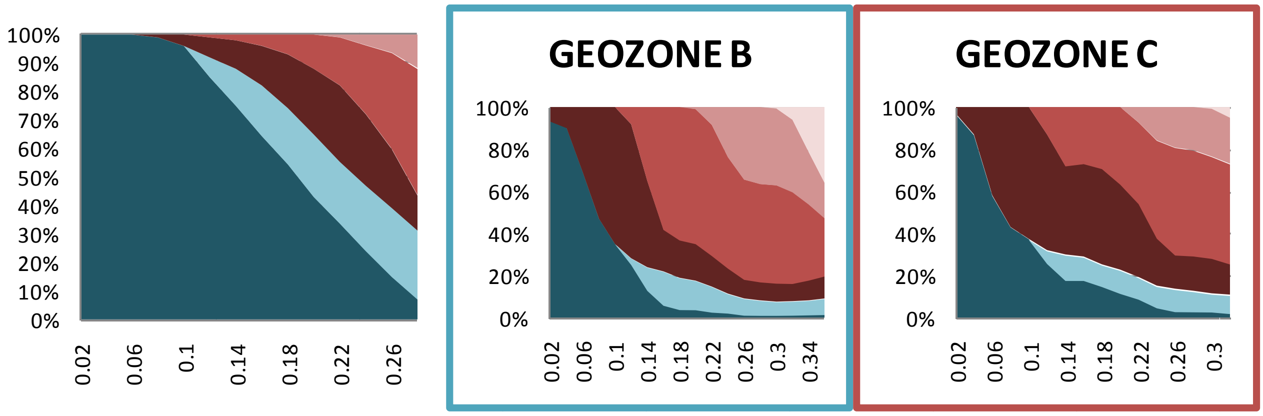


Figure 3.27 Site E9LON

3.6.2 Geozone D

Site Crocodile 1 (Figure 3.28), Site Crocodile 7 (Figure 3.29), Site Mokolo 3 (Figure 3.30) and Site Outeniqua 3 (Figure 3.31). Other than Outeniqua 3, the desktop and workshop results produce similar fast habits, a bit more or less in certain cases but acceptable within the expected ranges of uncertainty, with the loss of each habitat decreasing and ceasing at similar rates. Outeniqua 3 desktop result produced greater fast shallow habitat and no fast intermediate or deep habitats with FS being lost at a similar flow depth.

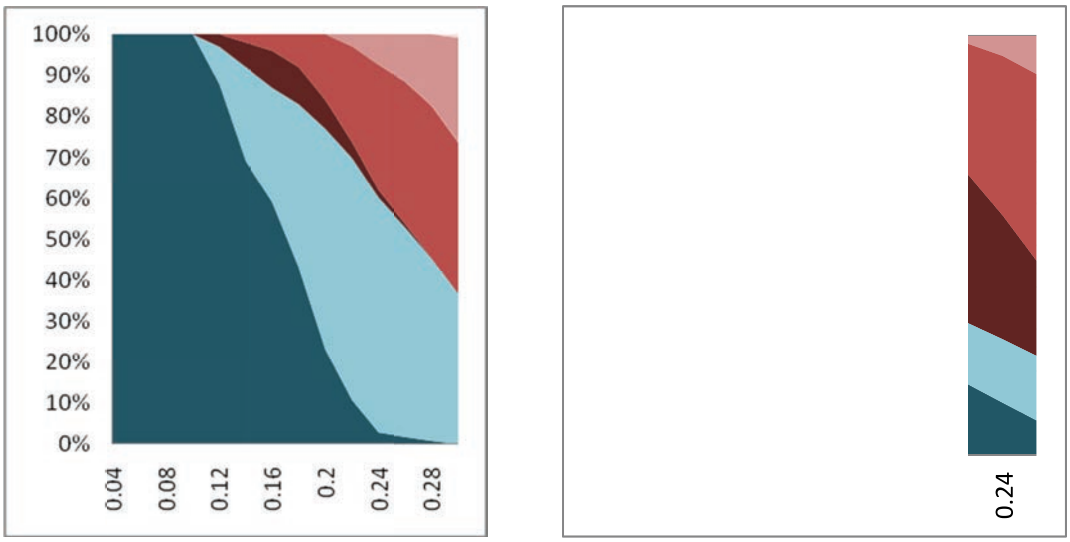


Figure 3.28 Crocodile 1 (Workshop; Right side, Desktop; Left side)

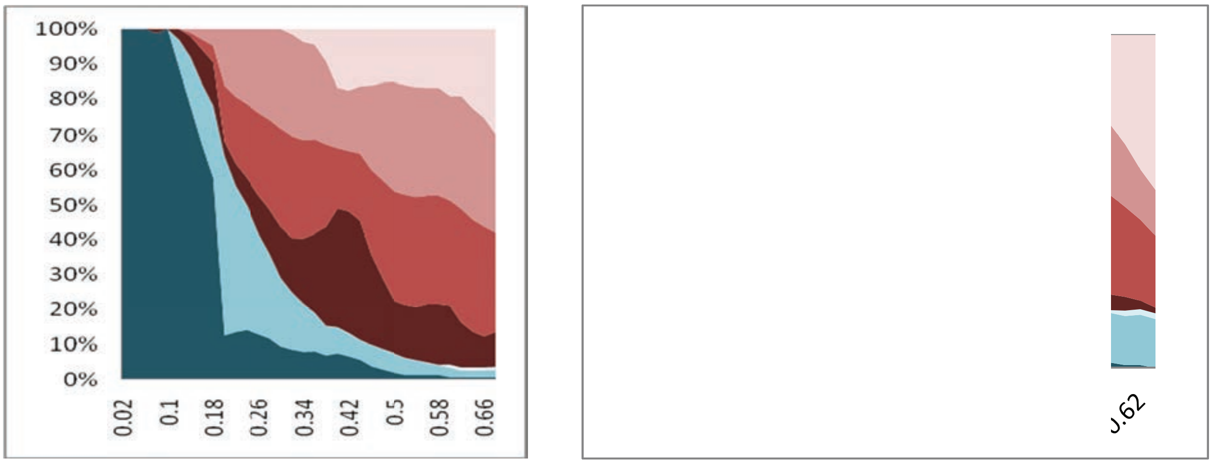


Figure 3.29 **Crocodile 7 (Workshop; Right side, Desktop; Left side)**

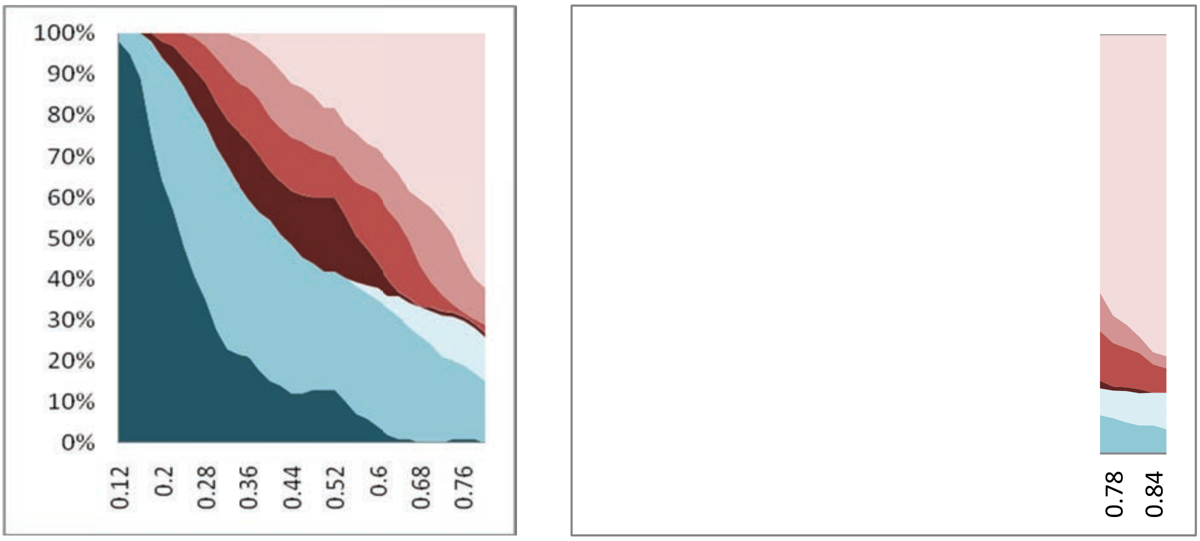


Figure 3.30 **Mokolo 3 (Workshop; Right side, Desktop; Left side)**

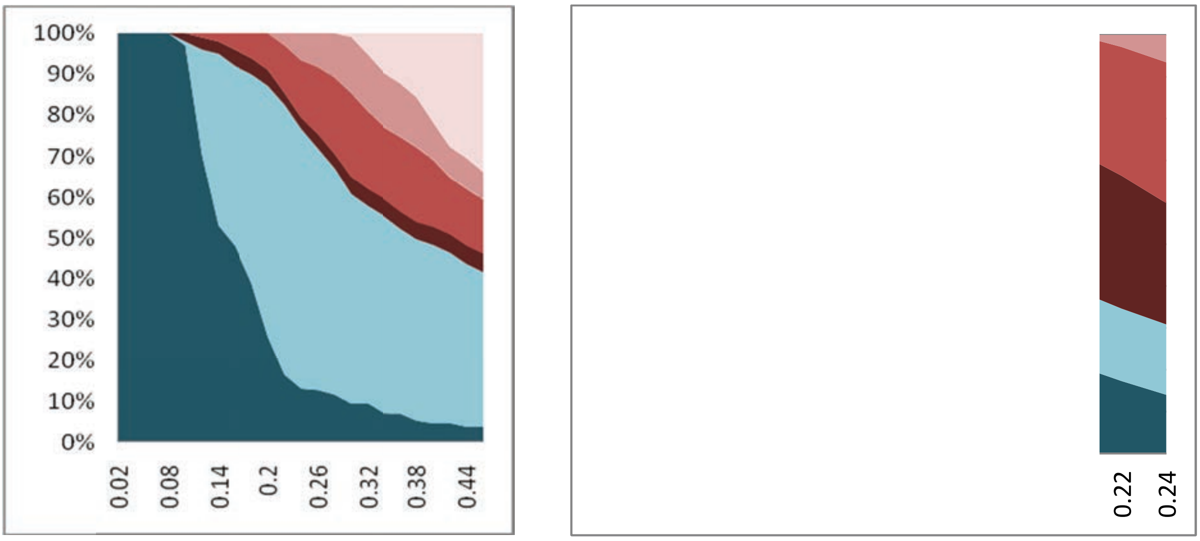


Figure 3.31 **Outeniqua 3 (Workshop; Right side, Desktop; Left side)**

3.6.3 Geozone E

Site Crocodile 4 (Figure 3.32), Site Crocodile 6 (Figure 3.33), Site Vaal 4 (Figure 3.34), Site Vaal 11 (Figure 3.35) and Site Mokolo 2 (Figure 3.36). Other than Mokolo 2, the separations between slow and fast habitats were reasonably well reproduced by the desktop model. Crocodile 4 desktop results produced less FD habitat but the other sites' desktop results produced acceptable habitats but the habitats disappear at lower depths than the workshop results. Significantly more fast habitats were produced in the desktop model for Mokolo 2 and may be due to the simplification of the estimated cross-sectional profile.

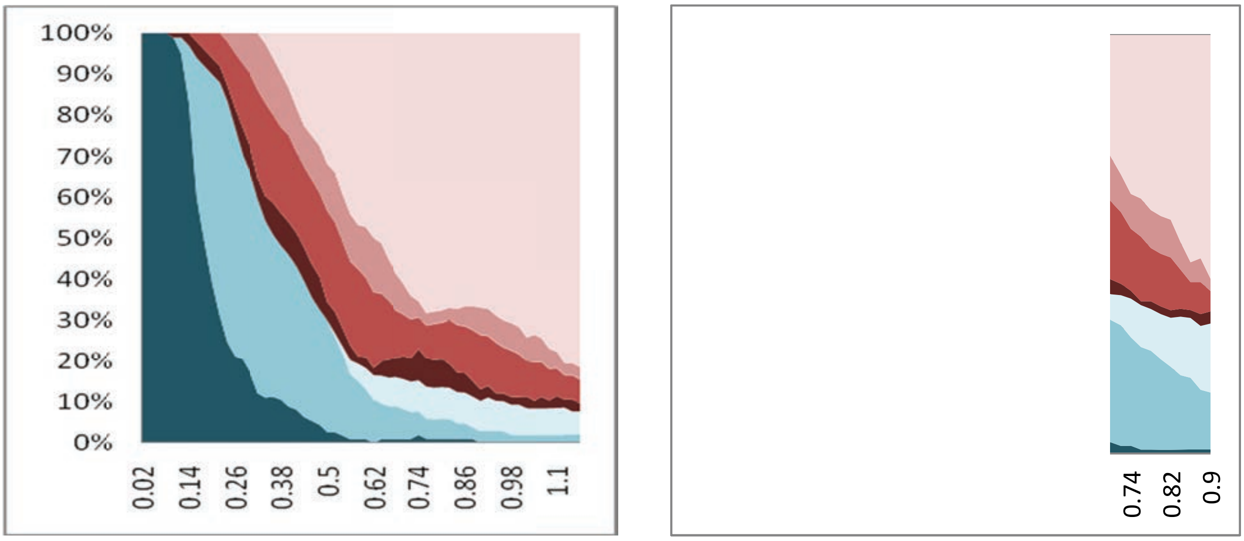


Figure 3.32 Crocodile 4 (Workshop; Right side, Desktop; Left side)

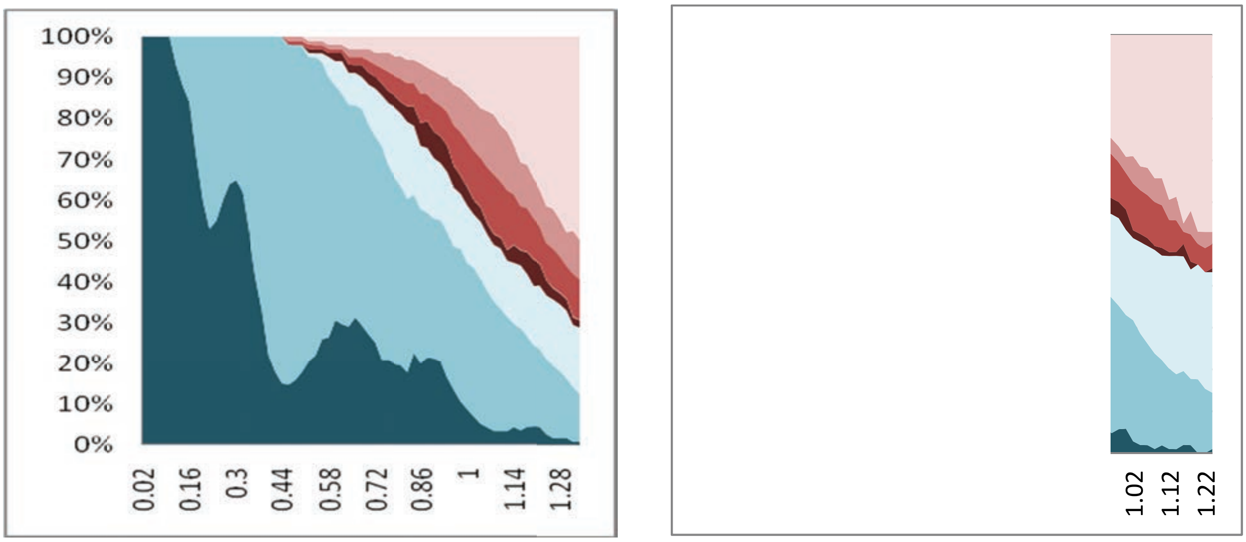


Figure 3.33 Crocodile 6 (Workshop; Right side, Desktop; Left side)

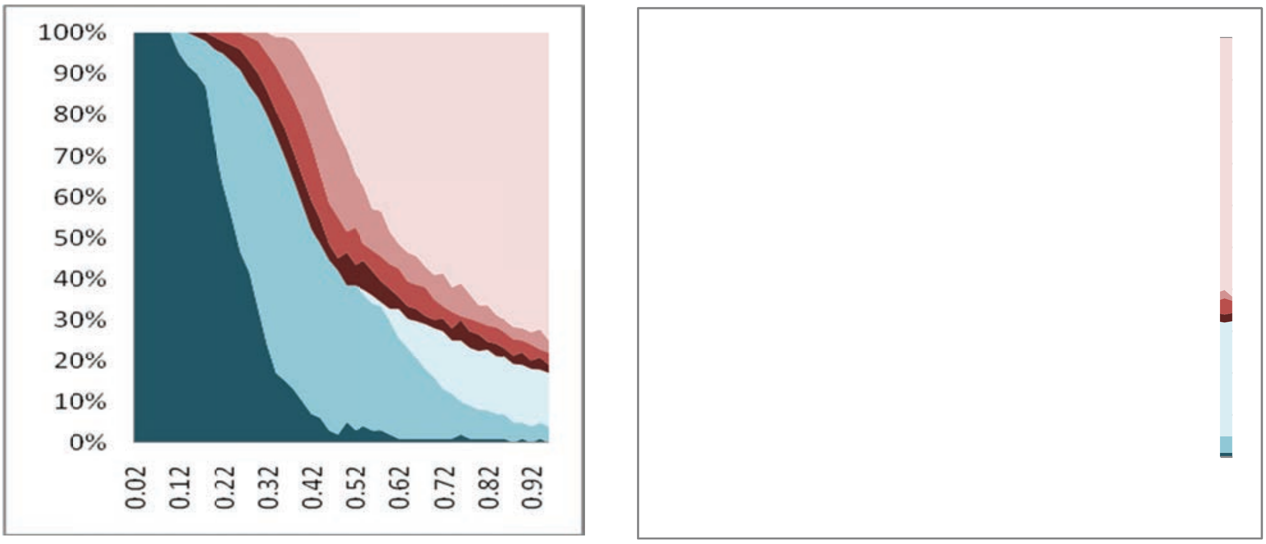


Figure 3.34 **Vaal 4 (Workshop; Right side, Desktop; Left side)**

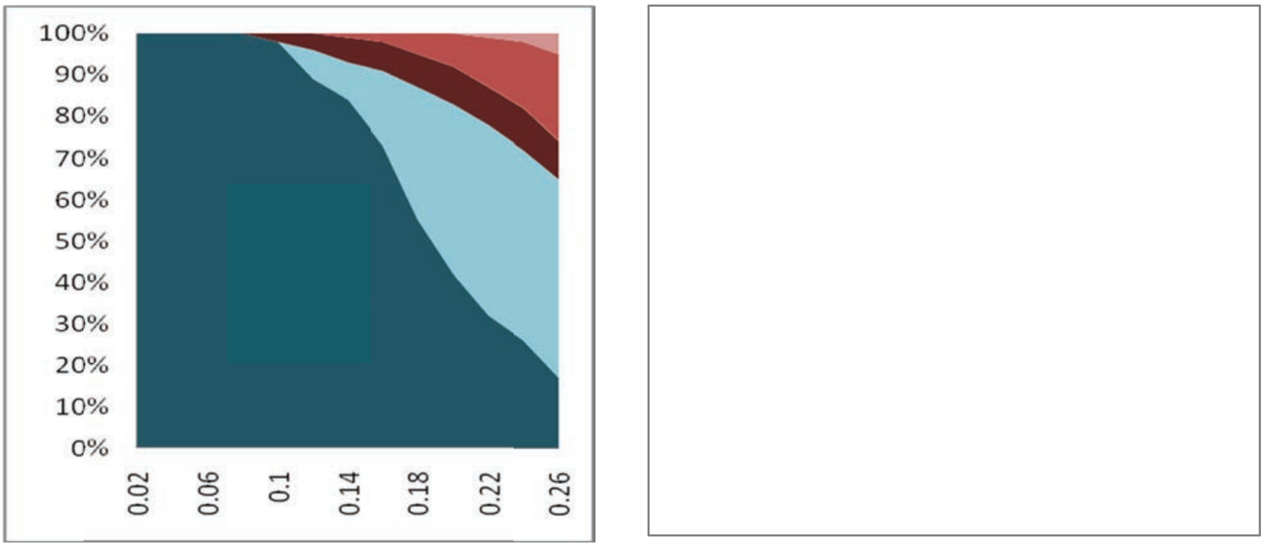


Figure 3.35 **Vaal 11 (Workshop; Right side, Desktop; Left side)**

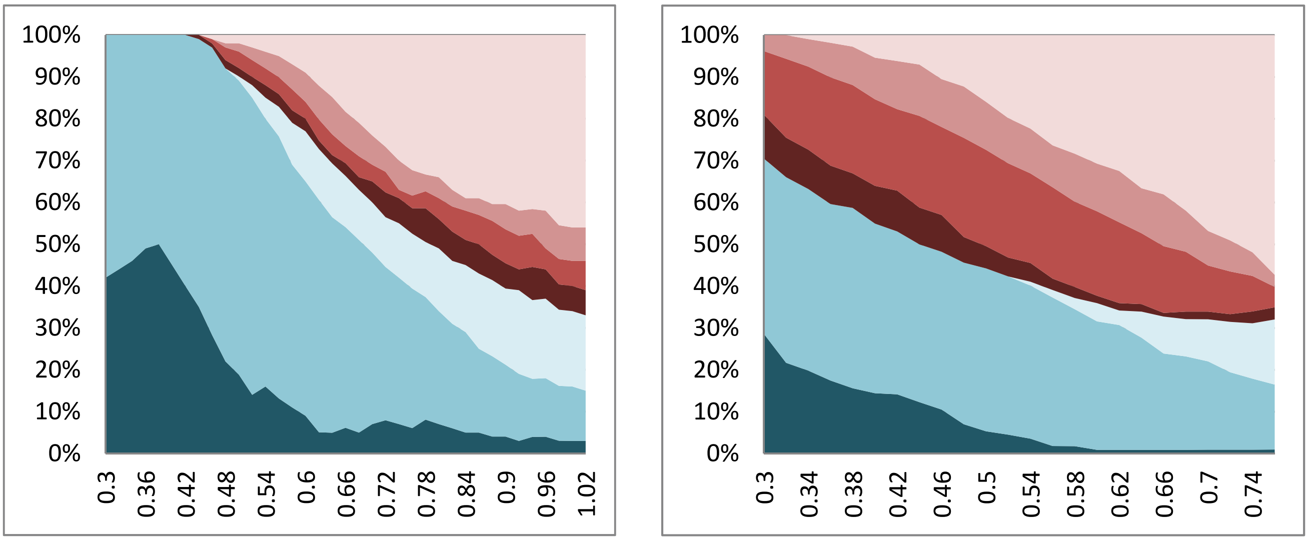


Figure 3.36 Mokolo 2 (Workshop; Right side, Desktop; Left side)

3.6.4 Geozone F

Site Vaal 1 (Figure 3.37), Site Vaal 2 (Figure 3.38), Site Vaal 5 (Figure 3.39), Site Vaal 8 (Figure 3.40) and Site Mokolo 4 (Figure 3.41). The desktop results are dominated by slow habitats. In the fast habitats, FD is the dominant habitat class with little or no FI and FS habitats. The reason for the misrepresentation of habitat classes between the desktop and workshop results is due to the difference between highly stepped observed cross-sectional profiles, which result in local energy gradients and the potential for higher velocity flows, estimation and simplified estimated cross-sectional profiles. Geo-zone F sites were always expected to be difficult to simulate for reasons associated with the site selection process and the need to identify riffle or run type sites which may not be entirely characteristic of F Geo-Zones.

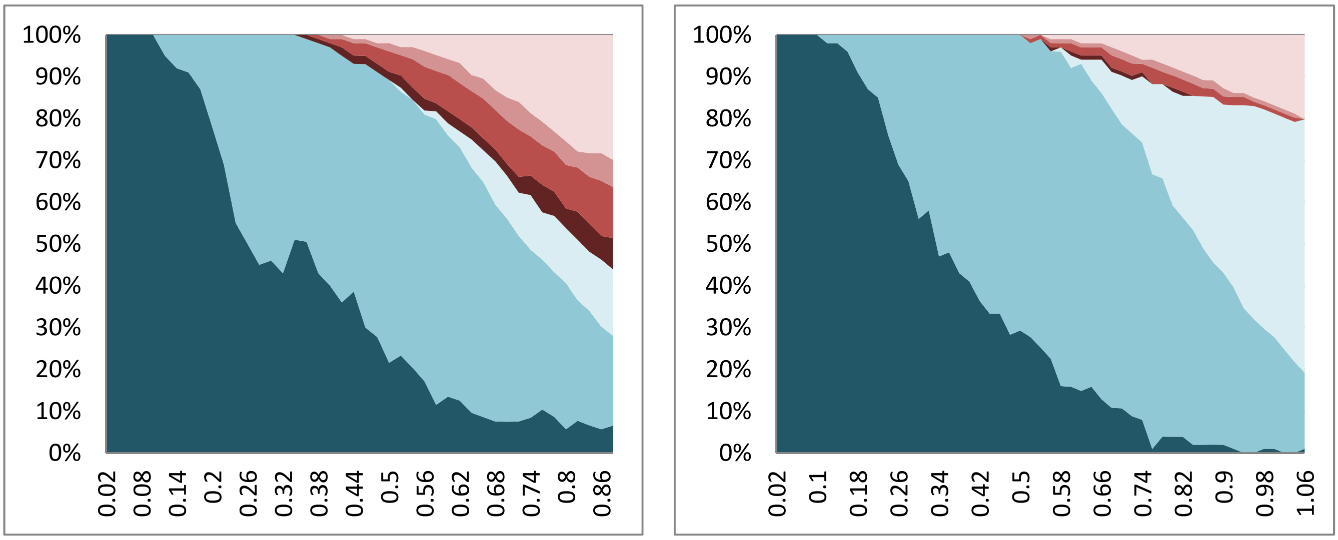


Figure 3.37 Vaal 1 (Workshop; Right side, Desktop; Left side)

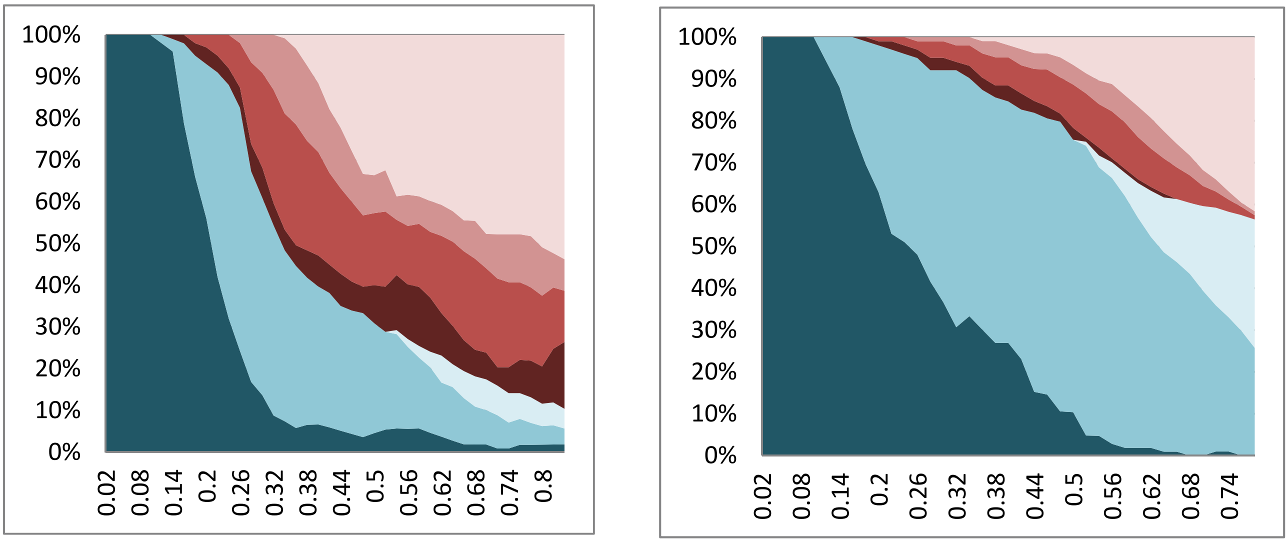


Figure 3.38 Vaal 2 (Workshop; Right side, Desktop; Left side)

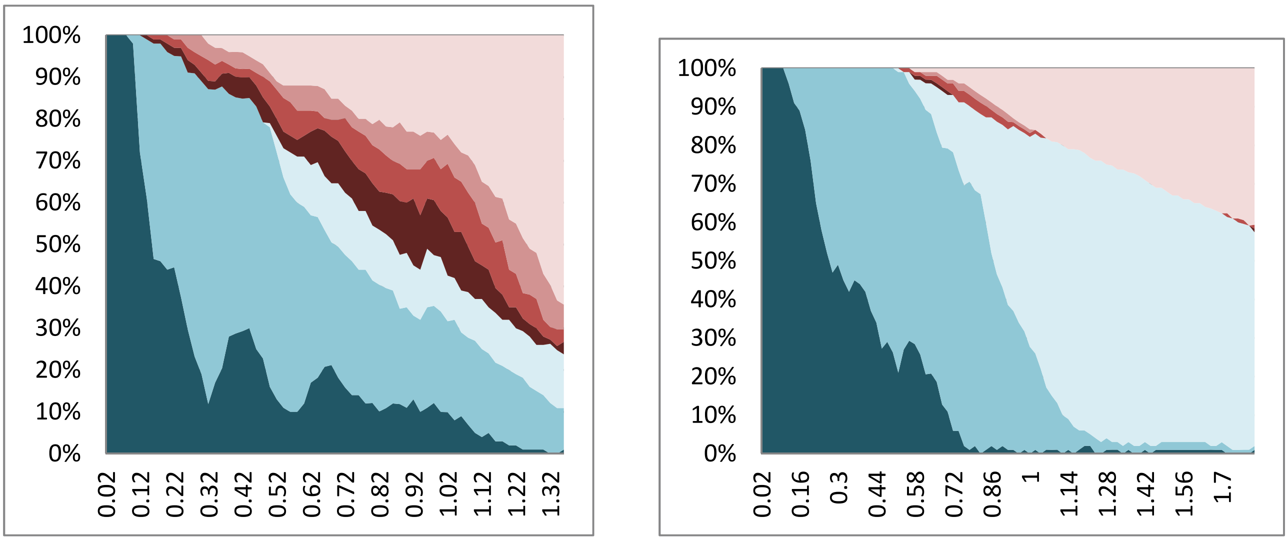


Figure 3.39 Vaal 5 (Workshop; Right side, Desktop; Left side)

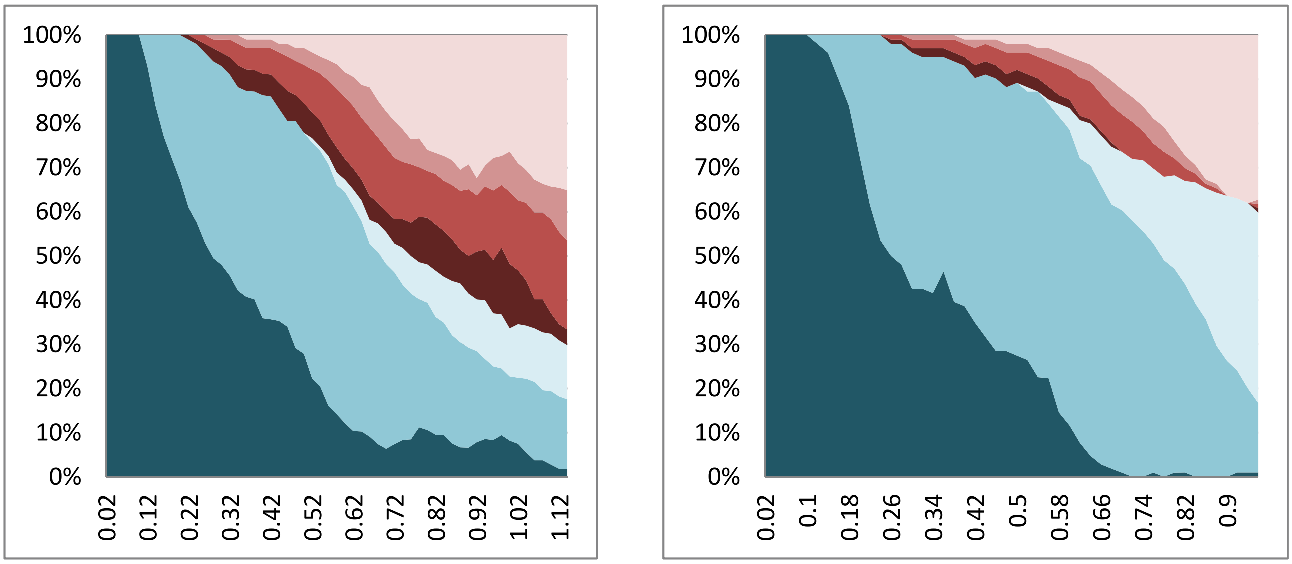


Figure 3.40 Vaal 8 (Workshop; Right side, Desktop; Left side)

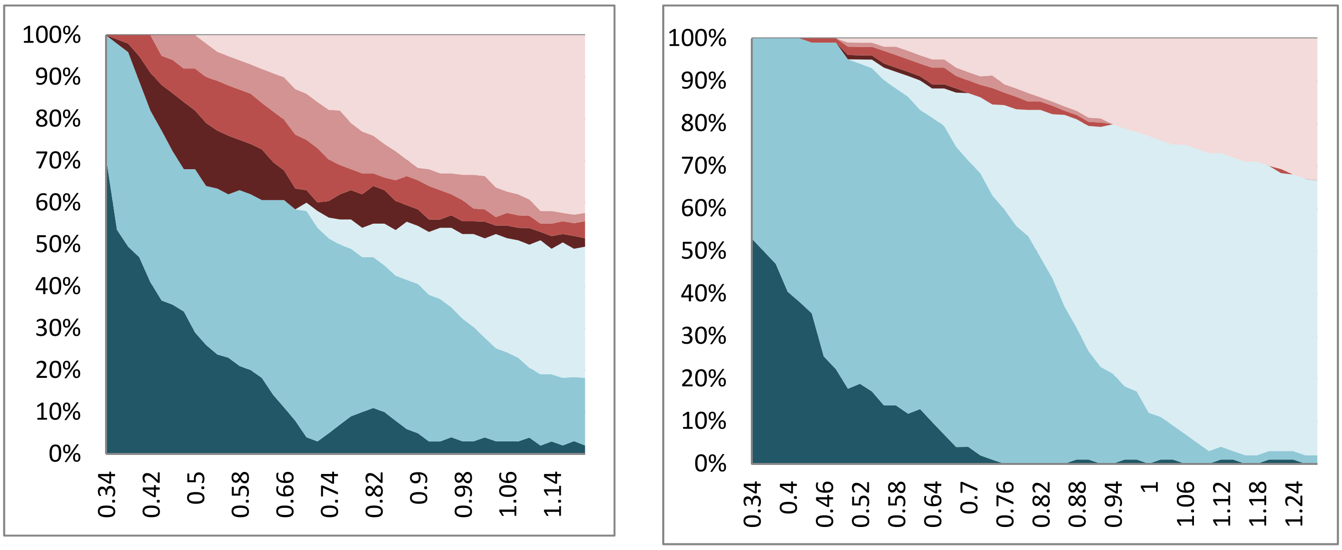


Figure 3.41 Mokolo 4 (Workshop; Right side, Desktop; Left side)

The habitat comparisons presented in this part of the report highlight some of the uncertainties associated with using a desktop approach to defining channel cross-section geometry and hydraulic parameters. The fact that there will be differences in the rating curve shapes between the workshop and simulated results may also compensate for the differences in the habitat – depth relationships. It is difficult to determine the real cause of these differences but is likely to be due to the over-simplification of the cross-sections in the model compared to the observed sites.

Overall, the habitats obtained using the desktop model was found to be acceptable within the accepted ranges of uncertainty. The major differences occur in the distinction between fast deep and fast intermediate habitats. This is not a critical issue with respect to the links with the ecology sub-model, but may be suggestive of some deficiencies in the model cross-sections and hydraulic parameters. One possible problem is that the workshop results tend to suggest that fast habitats disappear at deeper depths while the desktop results suggest that fast habitats are present at very shallow depths.

Some of the results suggest that the model is not very sensitive to the selection of the correct Geo-zone. Changes in the Geo-zone will mainly affect the channel width/depth ratio and it is useful to understand that small changes in this ratio will not affect the habitat relationship.

4 THE REVISED DESKTOP RESERVE MODEL (RDRM)

This part of the report represents a preliminary version of the user manual for the Beta version of the model. However, it should be recognised that additional user guidelines will almost certainly need to be added as the software is used by a range of different users and as experience is gained in different river systems. This chapter is therefore a copy of project Deliverable 9 and it is expected that it will be updated as the need for additional guidelines emerge. As already noted in the introduction to this report, some of the details of the algorithms used in the model are documented in this section. These have been included so that users can become better informed about how certain parts of the model generate the results, but also to capture some of the more complex details of the model to provide future developers with a basis for modifications.

4.1 AN OVERVIEW OF THE MODEL AND ITS DIFFERENT COMPONENTS

The model is implemented as part of both the original SPATSIM framework and the updated SPATSIM-HDSF and consists of 5 main components (see Figure 4.1); the hydrology sub-model, the hydraulics sub-model, the ecological sub-model, the process for adding high flows or flood volumes and the process for integrating all the components to generate the Reserve requirements as assurance rules or time series. ***It is assumed that users of this model will have an understanding of the basic functionality of running a SPATSIM (or SPATSIM-HDSF) application (loading and editing attribute date, setting up models, etc.) and therefore instructions on how to operate SPATSIM are not included in this report.***

In general terms, users are reminded that they can zoom in (click the mouse on the graph area, hold down and drag right and down) and zoom out (click the mouse on the graph area, hold down and drag left and up) on all the graphs displayed within the model. Panning within a graph is achieved by right clicking, holding down and moving the mouse left or right.

All of the components have reporting facilities that allow the key information to be saved and later written to either a text file or a SPATSIM memo attribute, or both. There are relatively few user interventions, but where these occur they are explained in the following sections. These interventions are designed to allow the user some choice in how the input data are interpreted and how the Reserve requirements are set. In most cases though, the default options are expected to give an acceptable result. There are, however, one or two situations where informed choices are required to generate satisfactory results. Guidance is given where necessary in the following sections.

While the model has been quite extensively tested across a range of different sites (with respect to catchment size, climatic characteristics, etc.), it is possible that some unique situations where the model will not work properly have been missed. During the testing it has already been noticed that there are some parts of the model that need to be refined to account for special cases, but these refinements have yet to be made. Where these types of situations have already been identified they are highlighted in the following sections so that users may be able to identify them more easily when they occur.

4.1.1 Differences between the RDRM and the previous Desktop Reserve model

The main difference between the two models from a scientific point of view is that the RDRM model explicitly includes some links between hydrology, hydraulics and ecology (Hughes and Louw, 2010), while the previous desktop model (Hughes and Hannart, 2003) merely included implicit links between the degree of hydrological variability and the ecological water requirements of rivers. A further fundamental difference is that the previous model was firmly entrenched in the principles of the Building Block Methodology (King and Louw, 1998), despite extending the original BBM concept of ‘maintenance’ and ‘drought’ flow requirements to include the full range of flows with different assurances through the use of regionalised magnitude-frequency relationships (Hughes, 1999; Hughes and Hannart, 2003). From a user’s point of view the main difference in the outputs are therefore that the old ‘.tab’ files no longer exist, while the assurance rules contained within the old ‘.rul’ files are retained as part of the output of the RDRM. This development should avoid much of the confusion that arose in the past from the interpretation of the outputs. In the previous model, it was never possible to determine what the long-term mean annual Reserve requirement would be from the ‘maintenance’ and ‘drought’ flow requirements listed in the ‘.tab’ files. This is because the regionalised assurance rules were quite complex and highly variable across different regions and different months and these rules defined the relationships between the BBM ‘maintenance’ and ‘drought’ requirements and the long-term mean. In the RDRM the final output consists of the long-term mean Reserve (which can then be compared to the long-term mean natural and present day flow volumes), together with the monthly assurance rules (which can be compared to the flow duration curves of natural and present day flows). Both of these outputs are available for the Reserve with and without the inclusion of high flow requirements.

The final difference between the previous Desktop Reserve model and RDRM is that there are less user interventions included in the current version of the RDRM. The Desktop model was used quite frequently to support intermediate and comprehensive Reserve determinations in which the model outputs were ‘calibrated’ against some of the detailed Reserve requirements set by specialists. The model therefore required many options for changing the results, options that would not be normally used when the model was applied without specialist input. The revised model has not been designed for this purpose, although it is accepted that it will be used with detailed Reserve determinations in the future. It is likely that additional components will have to be added to improve the flexibility of use of the RDRM, but the current version only includes a few options for user intervention. This is, of course, an advantage for inexperienced users as they are able to obtain a default result without having to make any major decisions (which they may not be experienced enough to make with confidence).

4.2 THE INPUT/OUTPUT DATA REQUIREMENTS

The model is set up in exactly the same way as any other model in SPATSIM, by associating attribute information contained within a SPATSIM (or SPATSIM-HDSF) application with the model input/output requirements. Some of the optional requirements have not been implemented in the current version of the model but have been retained for future possible developments. The input requirements consist of:

- Site name: a text attribute simply containing the name of the Reserve site for identification purposes.
- Single Parameter Data: an array attribute that is the same as the attribute of the same name used in the original Desktop Reserve model. The only parts of the data table that are used in the RDRM are the two parameters of the monthly baseflow separation method (Hughes, Hannart and Watkins, 2003) used as part of the hydrology sub-model (the last two parameters in the list and referred to as 'BF Alpha' and 'BF Beta'). These are regionalized values and the National RDM database contains appropriate values as part of the Desktop Single Parameter data table. As noted in the hydrology sub-model section (4.3 of this report) the user may wish to change these two parameters (using the edit attribute data facility in SPATSIM) if the results of the baseflow separation analysis are not considered to be appropriate.
- Natural Flow Data: a time series attribute containing either observed or simulated natural flows for a reasonable length of time (typically greater than 50 years). There should be no missing data within the time series.
- Present Day Flow Data: a time series attribute containing representative present day flows for a reasonable length of time (typically greater than 50 years). The length of record should be the same as the natural flow data.
- Regional Hydraulic Model Parameters: an array attribute containing the main parameters of the hydraulic sub-model (further explained in the section of the report that deals with that sub-model).
- There are two options for a surveyed channel cross-section and a calculated stage-discharge curve, but the use of these has not been implemented in the current version of the model.
- A flood requirement table attribute has been included so that specific flood requirements can be added (rather than using the internal default estimations). However, this part of the model has not been implemented yet.

The output attributes are:

- Total Flow Assurance Data: an array attribute that is used for saving the total flow (low flows and high flows) Reserve assurance rules for a specific Reserve category.
- Low Flow Assurance Data: an array attribute that is used for saving the low flow (no high flows included) Reserve assurance rules for a specific Reserve category.
- Total Reserve Requirement: a time series attribute that is used to save the time series of Reserve requirements. The user has the option to specify whether the high flows are included or not when the data are saved.

- Reserve Notes: a memo attribute that is used to save the report of the Reserve determination (which can also be saved to a text file during the running of the model).

Before setting up the model users should ensure that they have loaded (or edited) data for the key input requirements as follows:

- Site name: A text attribute that can be simply edited to add an appropriate name for the site.
- Single Parameter data: An array attribute that contains the baseflow separation parameters associated with a specific Desktop model region. This is the same set of parameters used with the old Desktop model and can be loaded from text files (single_1.txt to single_20.txt) supplied with the RDM National Database application of SPATSIM and SPATSIM-HDSF.
- Natural Flow Data: A time series array attribute populated by importing monthly flow data in the usual way.
- Present Day Flow Data: A time series array attribute populated by importing monthly flow data in the usual way.
- Regional Hydraulic Model Parameters: An array type attribute that can be mostly populated from data generated when the model is run, however, four rows should be populated by editing the array data before the model is run. These are the Geom. Zone (value between 1 and 6), Flood Region (value between 1 and 12), Valley Slope (a fraction) and Catchment Area (km^2). Guidelines for identifying the values of the first and third will be established in the near future. Until these are prepared, the user will be required to use other sources of information. An attribute that identifies the flood region associated with each quaternary catchment has been generated and added to the SPATSIM RDM National Database. Alternatively Table 4.1 can be used to select the appropriate flood region.

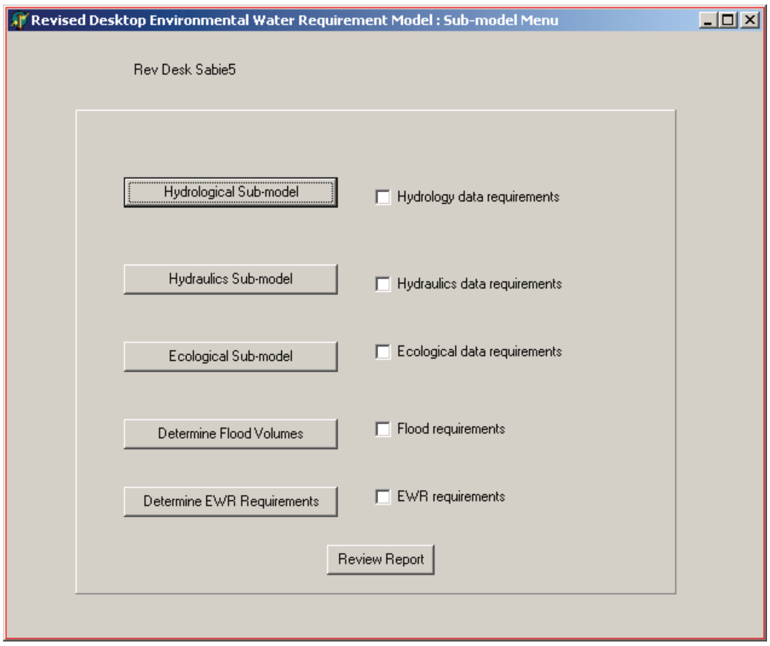


Figure 4.1 Main screen of the RDRM.

Figure 4.1 illustrates the main screen of the model after the input data have been loaded. The layout of the screen is designed to take the user through the various steps of running the model, which have to be run in sequence as data required for some steps are generated by previous steps. Users are not able to run some steps before the others are completed. However, it is possible to move around within the various steps to modify some of the results or to review some of the outputs.

A button on the main screen of the model (Figure 4.1) is available to view the report (see later) and to output the report to a text file (see Appendix A for an example).

4.3 THE HYDROLOGY SUB-MODEL

Figure 4.2 illustrates the first screen of the hydrology sub-model before the second part (using the 'Go to Graphics Plots') has been completed and therefore some of the data that are calculated have not been filled in. The top two blocks of information contain the summary statistics for the natural and present day flows (using much the same format as used in the old Desktop Reserve model). The lower block of data lists the percentages of total natural flow (at several pre-selected % points on the flow duration curve) that are assumed to be contributed by high flows (i.e. after the baseflows have been separated). It would normally be expected that the high flow contribution to total flows would decrease as the percentage exceedance value increases (i.e. the baseflow contribution to total flow increases as the total flow decreases, while the high flow contribution increases as the total flow increases).

It has already been noticed that the list of high flow % values given in the lower block do not always make a great deal of sense for seasonal or ephemeral rivers as trying to separate high flows from low flows is very uncertain in such situations. This has the potential to affect some of the results of the high flow requirement estimation process.

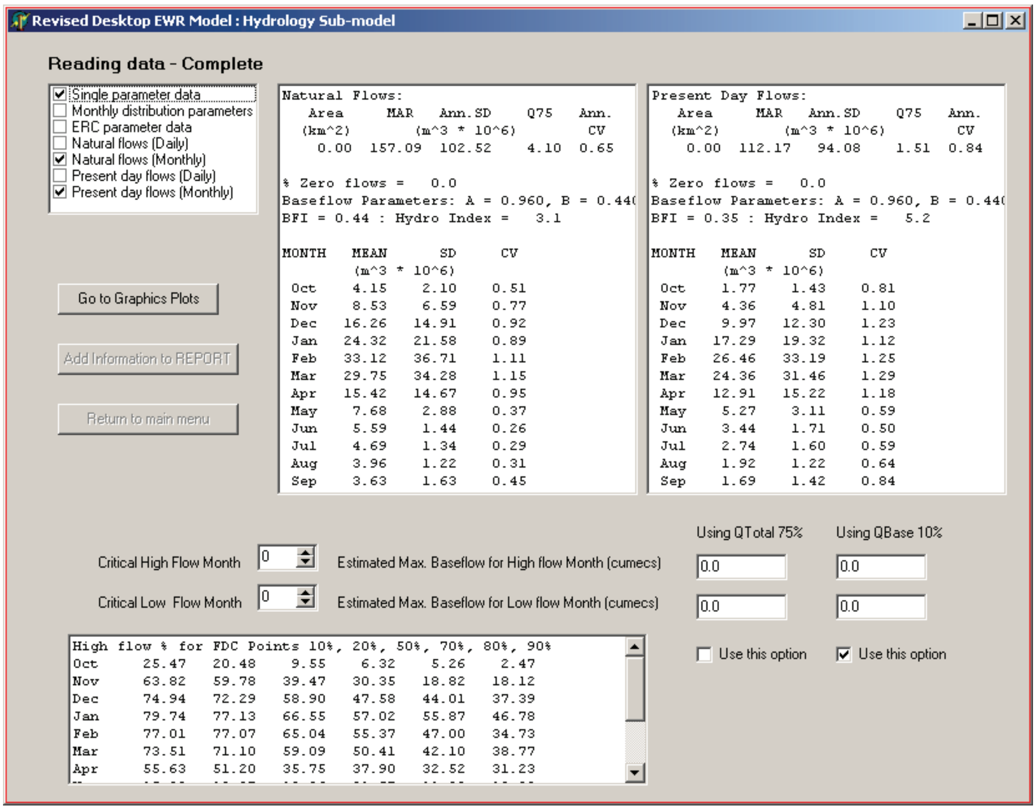


Figure 4.2 First screen of the hydrology sub-model (before analyses completed).

Clicking on the 'Go to Graphics Plots' brings up the screen illustrated in Figure 4.3 which represents the main hydrological analysis. The objective of this analysis is to identify the main wet season and dry season months and to quantify the maximum baseflow values for these two months. The top graph displays the time series of the natural and present day total flows, as well as the separated baseflows (using the separation parameters given in the Single Parameter Data attribute). The bottom left graph displays the same data as annual 1-month flow durations curves, while the bottom right graph displays the seasonal distributions of total and baseflow for the selected % point of the flow duration curve. The default selection is the 20% point (see the spin box above the red text information box on the left hand side of the screen). Changing the % point value and clicking on the 'Re-Draw' button changes the selection of the baseflow % point that will be used to determine the maximum baseflow for the other parts of the model. There are a limited number of % points that can be selected and if the user is not sure then accept the default value of 20%.

During the testing of the model an attempt was made to determine some guidelines for deviating from the default selection of the 20% point. It was noted that in some large rivers it was better to select the 10% point to match previously used maximum baseflows, while for smaller rivers using the 30% or 40% point appeared to give more sensible results. However, no general guidelines emerged from these tests. The most appropriate guideline is therefore to run through the model several times using between 10% and 40% and assess the differences in the final result. If the differences are small (i.e. the model is not very sensitive to changes in the maximum baseflow values used) then the default of 20% can be used. If the differences are large then the

user may need to make a personal decision or decided to offer a range of possible results as the final output.

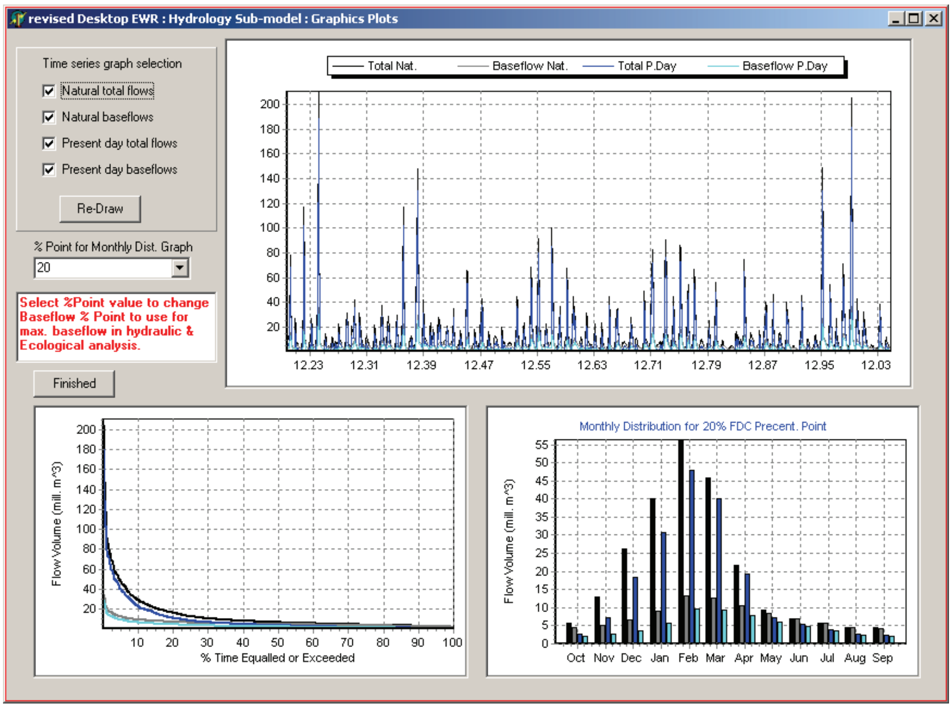


Figure 4.3 Second screen of the hydrology sub-model.

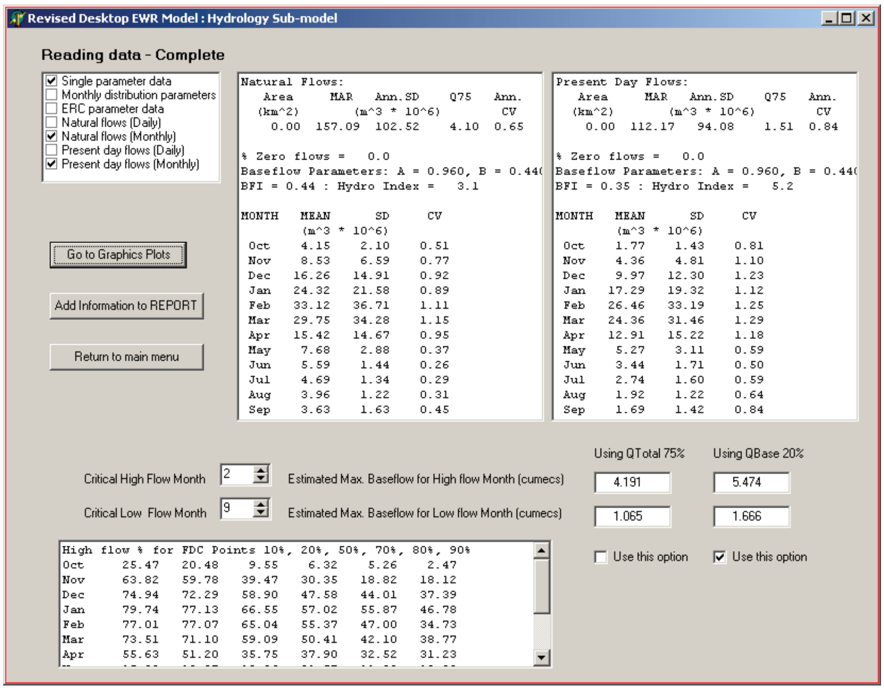


Figure 4.4 First screen of the hydrology sub-model (after analyses completed).

All of the graphs can be 'zoomed in' (click, hold down and drag the mouse down and to the right) and 'zoomed out' (click hold down and drag the mouse up and to the left). The different time series can be included or excluded from the graphs by clicking the relevant selection bullets (top left part of the screen.

On returning to the first screen of the hydrology sub-model (Figure 4.4) the critical high flow months are identified and the maximum baseflow values are entered into the display boxes at the lower right of the screen (Figure 4.4). Note that the baseflow value (QBase) is based on the selected % point (previous screen, Figure 4.3), while the total flow value (QTotal) is based on the 75% point of the total flow calendar month duration curve. The use then has the option to choose between which of these values will be used (for both wet and dry seasons) in the remainder of the model. ***The default option is the baseflow value (QBase) and users are recommended to always select this unless they have a very good reason for choosing the QTotal option.***

A final option available on the first screen of the hydrology sub-model allows the user to save a summary of the hydrology data and the analysis to a text memo (see 'Add information to REPORT' button). This button is also used to initiate the report that can be added to during the running of the other sub-models. ***This means that the report button must be clicked on the Hydrology sub-model page before reports can be generated from the other sub-models.***

It has already been noted that the outputs from the hydrology sub-model are very dependent on the parameters (BF Alpha and BF Beta) used in the baseflow separation equation that are included as part of the 'Single Parameter set' input requirement. The issue of separating baseflows and high flows in monthly time series data is fully discussed in Hughes et al. (2003) and the user is referred to this publication if there is any intention to review and edit the default regional parameters. There are facilities within SPATSIM (and SPATSIM-HDSF) to investigate the effects of changing the baseflow separation parameters (see the Baseflow Separation Calibration Model), but these should only be used by users who are familiar with hydrological time series analysis methods and who fully understand the concepts of baseflow separation methods.

4.4 THE HYDRAULICS SUB-MODEL

Figure 4.5 illustrates the screen of the hydraulics sub-model, the basis of which is described in a previous section of this report (Section 3). The parameter list on the left hand side of the screen lists the main parameters of the model that will either have been read in through the Regional hydraulic model parameter input requirement or will have been calculated by the sub-model (automatically the first time the model is run, or re-calculated by the user by clicking on the 'Re-Calc Parameters' button). The only information that needs to be quantified when the model is used for the first time at a new site is the Geom. Zone (integer value between 1 and 6 representing zones A to F), the Flood Region (Mkhandi's flood regions 1 to 13 – see Table 4.1 for guidelines), the valley slope (fraction) and the Catchment Area (km^2). The other values will be calculated. If the user entered valley slope is not compatible with the specified Geo. Zone it will be corrected and the user warned of the change that has been made.

The normal user interventions would be to change the values of the Geom. Zone, Flood Region, Valley Slope and Catchment Area and then click on 'Re-Calculate' and "Re-Plot Graphs' to update the estimations of the other parameters (then click on 'Save Parameters' to save the results back to SPATSIM for future use). If any of the other parameter values are changed the DO NOT click on the 'Re-Calc Parameters' button, but only on the 'Save Parameters' and 'Re-Plot' buttons. However, it will not be normal practice for a user to change any of the calculated parameters unless they are fully conversant with the hydraulics sub-model and the analysis methods used. The two graphs show the final cross-section (out of an uncertainty sample of 25) that has been generated by the model and the range of rating (or Stage-Discharge curves) generated by the 25 sample cross-sections. The latter graph includes the positions of the maximum baseflow values (from the hydrology sub-model) on the rating curve. The display box at top right provides some information about the mean annual flood and channel forming discharge that have been generated using the defined Flood Region and calculated Hydro. Variability (equivalent to the hydrological variability index used in the old Desktop Reserve model and calculated from the natural flows in the hydrology sub-model). To view this information it is necessary to click on the 'Re-Calc Parameters' button.

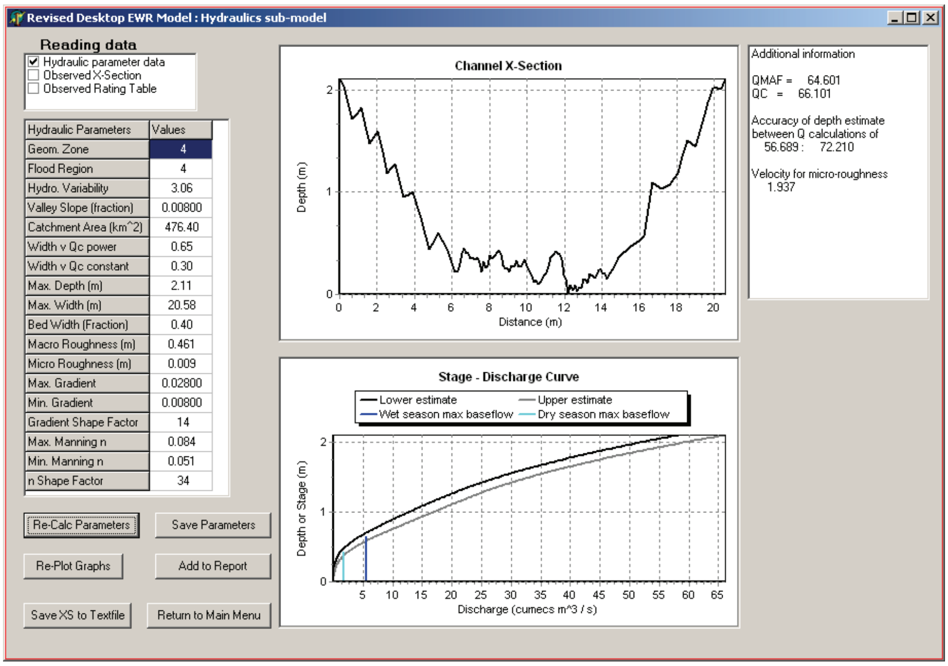


Figure 4.5 Screen of the hydraulics sub-model.

It has been noticed that (particularly for large rivers) the Mkhandi (Mkhandi and Kachroo, 1997) flood region equations do not always estimate an appropriate value for the mean annual flood (QMAF) and therefore the channel forming discharge (QC). These values have a large impact on the size and shape of the channel cross-section. It is possible that the user will have access to information that allows the estimated values to be checked (e.g. a nearby DWA stream flow gauging station with accurate flood discharge records). If the user identifies that the estimated QMAF appears to be too large or too small, it is recommended that the Flood Region number be changed until a more appropriate value is given. Remember to click on the 'RE-Calc

Parameters', 'Save Parameters' and 'Re-Plot' buttons before finalising the cross-section and hydraulic calculations.

Table 4.1 Mkhandi's flood regions (using the descriptions in Mkhandi and Kachroo, 1997)

Region	Tertiary catchments	Description
1	A1-A3	SW Transvaal bushveldt, NW Rand
2	A4-A7	NW Transvaal bushveldt
3	A8-A9 & B6-B9	NE Transvaal bushveldt
4	X1-X4	N of eastern lowveld, N of Drakensburg, SE Transvaal bushveldt
5	B1-B5 & C1-C9	S Transvaal bushveldt, highveld
6	W1-W3, W4, W5 & W7	Eastern lowveld, coastal plain
7	V1-V7	Eastern lowveld, central Drakensberg
8	R1-R4, S1-S7, T1-T9 & U1-U8	Eastern lowveld
9	D1-D3	S Drakensberg, S Highveld
10	P1-P4, Q6-Q9 & R5	Eastern Cape ranges
11	J1-J4, K1-K9, L1-L7, M1-M3 & N1-N4	Great Karoo, eastern part of Cape ranges
12	D4-D8 & F1-F3	Upper Karoo, Kalahari & Namib deserts.
13	E1-E4, F4-F6, G1-G4 & H1-H9	Western Cape ranges

A button is available ('Add to Report') that allows the user to save summary information to the report, while the 'Save XS to Textfile' allows the defined channel cross-section to be written to a text file for use in other software or a written report.

4.5 THE ECOLOGY SUB-MODEL

Figure 4.6 illustrates the appearance of the ecological sub-model. The basis of the model is the use of Flow-Stress relationships derived from hydraulic habitat data and the extrapolation of the natural stress frequency curves to stress frequency curves that are considered (at the desktop level of confidence) to be appropriate for the different Reserve categories. The basis of the method is therefore very similar to that used in intermediate and comprehensive determinations when the Flow-Stressor Response approach (now referred to as the Habitat Flow-Stressor Response model) is applied (Hughes and Louw, 2010).

One of the outputs of the hydraulics sub-model is the proportion of the channel occupied by different hydraulic habitats for all flows associated with water depths of 0.01 m up to the maximum channel depth. The proportions of the different hydraulic habitat types for the maximum baseflows in the identified main wet and dry season months is given in the upper right hand corner of the ecology sub-model screen. This information is used together with the maximum baseflow discharges and the hydrology time series to establish the natural flow-stress relationships for the two main months (wet and dry seasons). Zero stress is associated with the maximum baseflow discharges in the relevant months, while a stress of 9 is associated with the flow that results in at least some deep, intermediate or shallow habitat with fast flowing water (0.3 m s^{-1}). The remainder of the flow-stress relationships are based on the extent to which the proportions of the 'fast' (but not the very shallow fast) habitats decrease as the flow decreases from the maximum baseflow. The proportions of the different habitats that are available at the maximum baseflows for the wet and dry seasons are given in the display box at the top left of the screen (the months, water depths and discharges associated with these flows are given above the display box).

The use of the three 'fast' habitats (FD, FI, FS) is largely associated with the requirements for both large and small rheophilic fish guilds and as explained in Chapter 2 of this report these have been used as the basis for establishing the approaches of the ecology sub-model. The requirements for other biotic components (macro-invertebrates, riparian or in-channel vegetation, etc.) were found to be difficult to include at this stage of the development of the RDRM. However, it should be recognised that the fish requirements are only used to establish the natural flow-stress curves. It has already been noted that the model can still be applied even where rheophilic fish guilds do not occur. This situation can be identified when there is a high frequency of stress values over 9 (i.e. no FD, FI or FS habitats) under natural conditions. The critical issue is therefore that setting the Reserve requirements is based on the use of the three fast flowing habitats, the frequencies with which these occur under natural conditions and the frequencies with which they are expected to occur under managed conditions to achieve certain ecological conditions. Assessments of ephemeral and seasonal rivers can therefore be included as long as the criteria for setting environmental flows and the Reserve is based on the frequency of occurrence of at least some fast flowing (≥ 0.3 m s^{-1}) water with a minimum depth of 0.2 m (i.e. FS). This suggests that ephemeral river Reserve determinations (Hughes, 2005) based on the frequency of hydraulic connectivity (rather than the status of static pools) can be performed with the RDRM model. However, if other criteria are considered to be of importance then the RDRM model will probably not be the appropriate tool to use.

The use of a minimum depth of 0.1 m in the critical habitat specifications implies that the model will not be suitable for rivers where very shallow (but still flowing) water is important. The model is therefore not suitable for very small rivers. As with the situation for ephemeral and seasonal rivers, if none of the critical habitats occur in either of the two main months then the flow requirements for that month are assumed to be zero for all ecological categories as the model is not able to calculate the natural flow-stress relationship.

The analysis is started (and repeated if changes are made) by clicking on the 'Process Data' button. This displays the following information:

- The Flow-Stress relationship curves for the wet and dry seasons (top middle).
- The Stress frequency curves for the wet season for natural and present day conditions and for A, B, C and D category Reserves (middle bottom).
- The Stress frequency curves for the dry season for natural and present day conditions and for A, B, C and D category Reserves (middle bottom).
- The flow duration curves for natural and present day and for the 4 Reserve categories for either the wet or dry season month (based on the season selected in the middle left option – 'Season for FDC Plots'). The Reserve curves are generated by linking the stress frequency curves with the Flow-Stress relationships.

The critical part of the analysis is the upward shifting of the category stress frequency curves from the natural curve to the curves for the different Reserve categories. Table 4.2 lists the fractional 'shifts' of the two ends of the natural stress frequency curve (SFC) for the 6 ecological categories. SHIFTE applies to the high stress end of the curve, while SHIFTC applies to the low stress end of the curve. There are four main steps in the calculation of the Reserve category curves, while there are also two options to modify the default rule base. The first option refers to aligning the shifts at the high stress end of the curve to the present day stress characteristics (options available in the lower left part of the screen – Figure 4.6). The second option relates to perenniality and essentially determines whether a stress of 10 (zero flow) can occur in one or more seasons or not.

A button has been added ('Edit Shifts') that allows the user to modify the basic shift information. While it is not recommended that these values be changed by the average user, it is possible that they can be used to align the stress frequency curves with some prior objective (such as the present day stress frequency curve). If they are changed the general rule is that the values should increase as the ecological category increases.

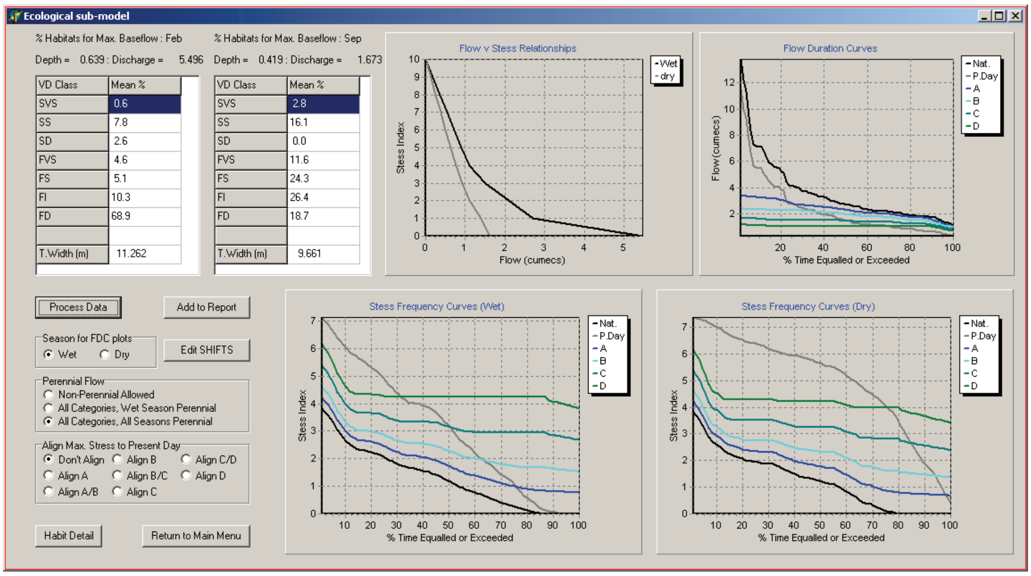


Figure 4.6 Screen of the ecology sub-model.

Table 4.2 Fractional shifts for category stress frequency curves.

Stress		A	A/B	B	B/C	C	C/D	D
High	SHIFTE	0.1	0.15	0.2	0.3	0.4	0.5	0.6
Low	SHIFTC	0.1	0.15	0.2	0.275	0.35	0.4	0.5

STEP 1 Establish a SHIFTE correction factor for perennial conditions

A shift correction factor is calculated if there is a requirement for perenniality in either of the two seasons (wet and dry). The shift correction is designed to ensure that the upper end of the SFCs does not exceed a stress of 10.

The initial value of the maximum stress for the category curve is calculated from the maximum natural stress and the SHIFTE value as:

CSmax = NSmax + NSmax * SHIFTE

If this exceeds a value of 9 for any category the correction (SCORR) is calculated as follows:

SCORR = 1 – ((9 + 0.1 * j – NSmax) / NSmax)/SHIFTE

with j set equal to 1 for the first category (starting with A) where CSmax exceeds 9. For the other categories j is incremented by 1 each time (see Table 4.3).

STEP 2 Establish frequency of zero natural stress

NSfreq0 is set to the frequency of the last occurrence (moving towards lower frequencies and higher stress values) of zero stress.

Table 4.3 Shift corrections example (based on a NSmax = 7.5)

Category	CSmax (initial)	Calculation	SCORR
A	8.25		0
A/B	8.625		0
B	9		0
B/C	9.75	1-((9+0.1*1-7.5) / 7.5) / 0.3	0.29
C	10.5	1-((9+0.1*2-7.5) / 7.5) / 0.4	0.43
C/D	11.25	1-((9+0.1*3-7.5) / 7.5) / 0.5	0.52
D	12.0	1-((9+0.1*4-7.5) / 7.5) / 0.6	0.58

STEP 3 Check for appropriate values of SHIFTC for a D category

This check is required to ensure that the SHIFTC and SHIFTE values are compatible with each other given the shape of the natural SFC. A point to the left of the zero point of natural stress is used to calculate an initial stress value for a D category, thus:

Freq = NSfreq0 – (100 – Nsfreq0) / 2

Check = NSmin + NSmin * SHIFTE(D) * (1 – (100 – Freq) * SCORR / 100)

Test = Check + (10 – NSmin) * SHIFTC(D) * Freq / 100

If the value of Test is greater than NSmax this means that the calculated high exceedance frequency stress values will be higher than the maximum calculated stress value, which is not sensible and needs adjustment. The adjustment is as follows:

SHIFTCnew(D) = NSmax – Check * 100 / ((10 – NSmin) * Freq)

And the SHIFTC values for the other categories are adjusted as follows:

SHIFTCnew(?) = SHIFTC(?) * SHIFTCnew(D) / SHIFTC(D)

STEP 4 Calculate the full SFC for all categories

Freq is set to the exceedance frequency (the X-axis of the curve) and this is used to spread the two shifts through the curve. The starting point is low frequency, high stress. Set the shift related to the upper (high stress) end of the curve:

SFreq = NSFreq + NSFreq * SHIFTE * (1 - (100 - freq) * SCORR / 100)

Add the shift related to the lower (low stress) end of the curve:

For the first point (lowest stress on the ecological category curve):

TF = NSfreq0 - (Freq – NSfrq0) / 2
SFreq = SFreq + (10 - NSFreq) * SHIFTCnew * TF / 100.0

For all other points

SFreq = SFreq + (10 - NSFreq) * SHIFTCnew * Freq / 100.0

Check if the current value of stress is higher than the last and if so set the value to the last stress value (i.e. create a flat part of the curve).

Check for stress greater than 10 and set to 10 if it is.

OPTION 1 Aligning SHIFTE for a specific category to the Present Day maximum stress

This option is allowed for so that the shift in the higher stress values can reflect drought or low flow conditions under the present day situation (see the available selections in the lower left part of the screen in Figure x.6). The selected category is used to re-calculate the appropriate SHIFTE value. If category C has been selected:

SHIFTEnew(C) = (PDSmax – NSmax) / NSmax

All the other SHIFTE values are adjusted accordingly:

SHIFTEnew(?) = SHIFTE(?) * SHIFTnew(C) / SHIFT(C)

STEPS 1 to 4 are then applied as above but using the SHIFTEnew values in place of the default SHIFTE values given in Table 4.2.

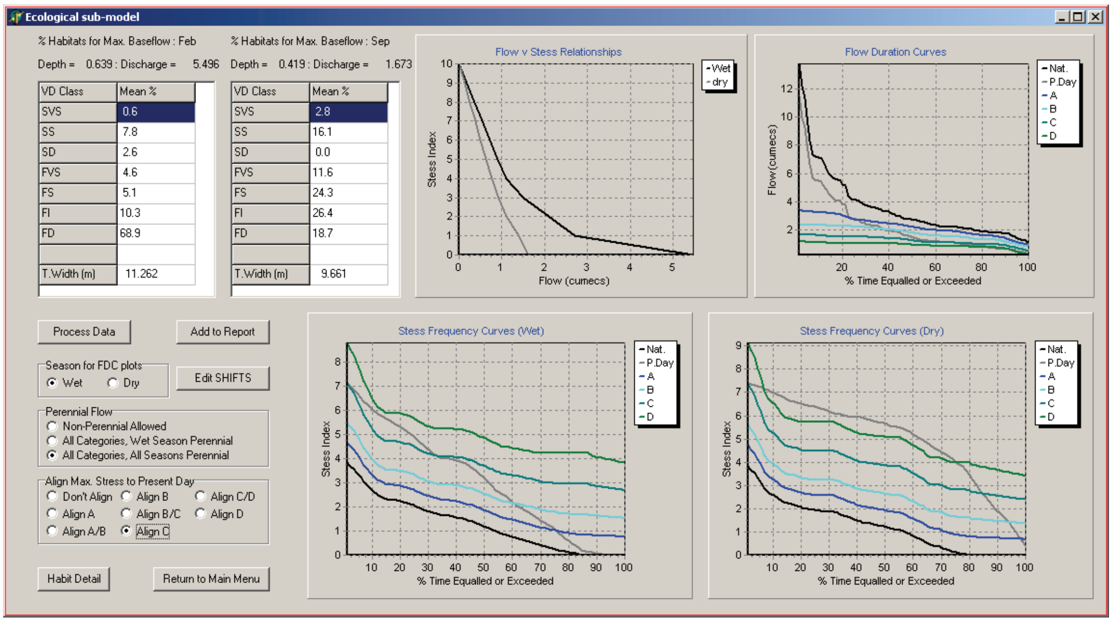


Figure 4.7 C category stress aligned to present day – Sabie River site example.

The effects of allowing for the two options (Perenniality and aligning to a specific category) are illustrated in Figures 4.7 to 4.10. Figure 4.6 includes the result for a site on the Sabie River that has relatively low stress values throughout the wet season, but where the present day maximum stress is 7. Figure 4.7 illustrates the effects of aligning the C category curve to the present day stress. The overall effect is to reduce the drought flow requirements, but will have little effect on the higher flows of the low-flow requirement flow duration curves. It can be seen from Figure 4.7 that the lowest flow requirements for a D category in the dry season will be almost zero (a stress of 9).

Figures 4.8 to 4.10 illustrate the effects of allowing (or not) for perenniality for a site on the Kromme River in the Eastern Cape Province. In Figure 4.8 it can be seen that the lowest flows are forced into a tight range to ensure perennial conditions while at the same time the maximum stress for natural conditions is over 7. Under present day conditions it is apparent that zero flow (stress of 10) occurs for more than 20% of the time.

Figure 4.9 illustrates the result when only the wet season is forced to be perennial. Under these conditions zero flows start to occur in the B category dry season (very small % of time), while in the D category they would occur some 40% of the time in the dry season. The final diagram (Figure 4.10) illustrates the result of removing the perennial constraint in both seasons. Under these conditions zero flows also occur in the wet season for C (some 7% of the time) and D (some 15% of the time) categories. The recommendation for zero flows in the wet season can also be seen in the flow duration curves at the top right of the screen shot in Figure 4.10.

The two options are relatively simple to apply. The perenniality option would be informed by the shapes of the natural stress curves and how close they are to a stress of 10 at the maximum stress end of the curves. The perenniality of the present day situation may also assist in making a decision about whether to apply perenniality to the category curves.

Aligning the maximum stress of one of the category curves to the present day situation would largely depend on how much is known about the present ecological state (and whether it is strongly related to the present day flow regime or some other effects).

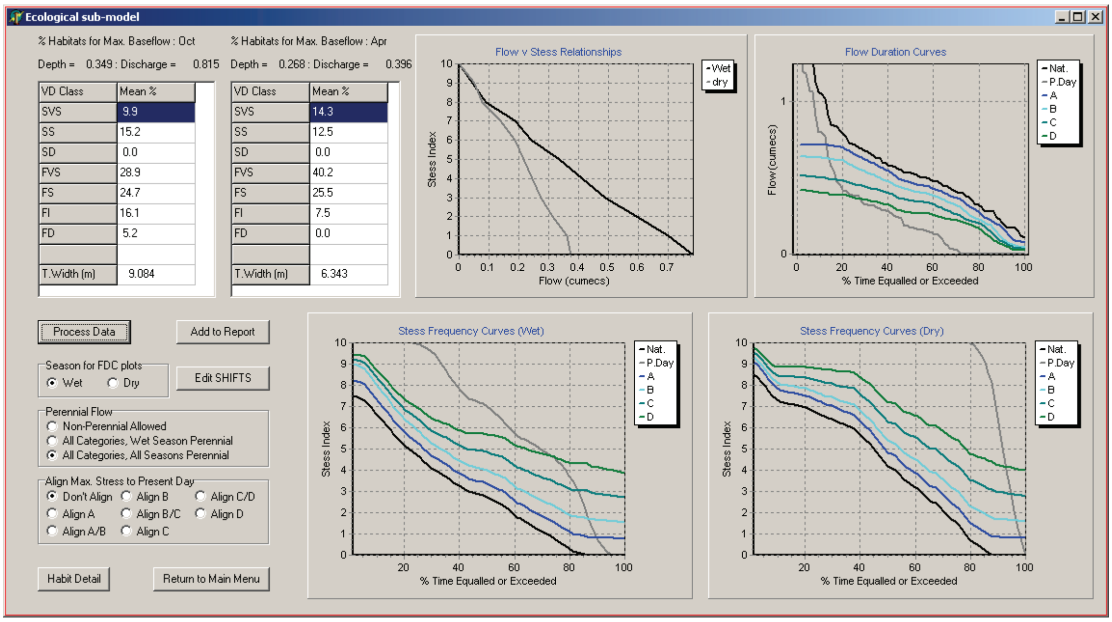


Figure 4.8 Kromme River site: All Categories, All Seasons Perennial.

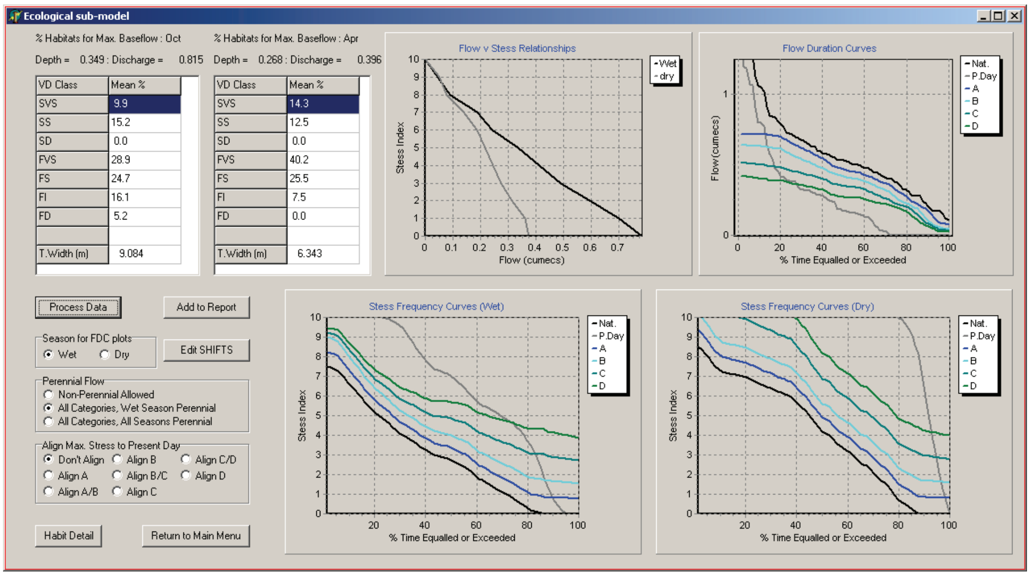


Figure 4.9 Kromme River site: All Categories, Wet Season Perennial.

The screen images of the ecological sub-model indicate that there is one other button that can be used to modify the results. The 'Edit Shifts' button allows the default shift factors (Table 4.2) to be modified by the user (the 'Process Data' button would need to be clicked to repeat the analyses and view the results). This option needs to be applied with caution as some strange results can occur under some situations. It must be recognized that the whole method of shifting stress from the natural condition to the different categories is a very new approach for a Desktop model that requires further testing before proper guidelines can be made available. Some of this testing has been done as part of the project (reported in Section 5 of this report), but these tests only covered a limited number of sites. It is therefore recommended that the default shifts with only the perenniality and maximum stress alignment options are applied under normal circumstances and that any further user interventions in the setting of the shift factors should await further testing by Reserve specialists.

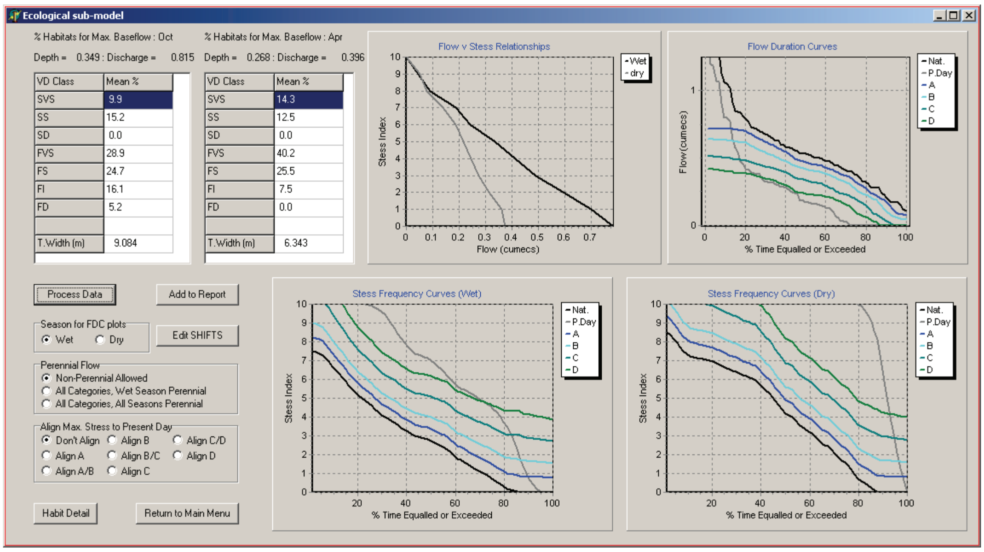


Figure 4.10 Kromme River site: Non-Perennial allowed throughout

As with the other sub-models, an option is included to add information generated by the ecological sub-model to the report for later saving or printing.

During the testing phase of the model a number of issues with relatively dry and/or small rivers were identified and this resulted in some modifications to the estimation procedures for the stress frequency curves in special cases (i.e. they do not affect the approaches discussed above in most rivers). When the Fast Deep (FD) habitat class at the maximum baseflow for the wet season is zero, the method of calculating stress is based solely on the Fast Intermediate (FI) and Fast Shallow (FS) classes. The effect of this will be largely transparent to the user.

If all of the Fast (Deep to Shallow) habitat classes are zero (likely to happen for the dry season in seasonal rivers) then no flow requirement for any ecological category can be quantified and the assumption is that these will be zero flows.

Guidelines for selecting the perenniality options.

The default option is that both seasons are considered to be perennial, however, non-perenniality can be selected for the dry season or both seasons when the maximum natural stress is close to an index of 9 or when the present day situation (if available) suggests non-perenniality (i.e. a stress of 10 for some of the time). In the latter situation it is also possible to use the option to align one of the ecological categories to present day (see next set of guidelines).

Guidelines for selecting one of the alignment options.

This option is used to align the maximum stress (i.e. drought flows) to the present day situation and the main guideline is that the alignment category should be based on a knowledge of the present ecological state (PES) of the river. However, it is also possible to select several different options to see which one gives the best approximation to the complete frequency curve for present day stress. When the present day maximum stress is 10 (for either the wet or dry season, or both) it is impossible to calculate a true alignment of the high stress part of the curve and the user is recommended to try various options until satisfied that the results for a specific category are appropriate.

Guidelines for changing the low stress ends of the frequency curves.

The only way to modify these parts of the curve is to edit the low shift factors (using the 'Edit Shifts' button). If it required that the ecological category stress curves should be moved downwards (closer to natural stress values) then these values should be reduced. The gaps between the shift values for different ecological categories can also be changed to bring the different curves closer together (decrease the gaps and therefore make the flow requirements for the ecological categories more similar), or further apart (increase the gaps and make the flow requirements more different). Any changes made will be saved and used during the current run of the model (and are written to the report), but will be lost if the model is closed and re-opened later.

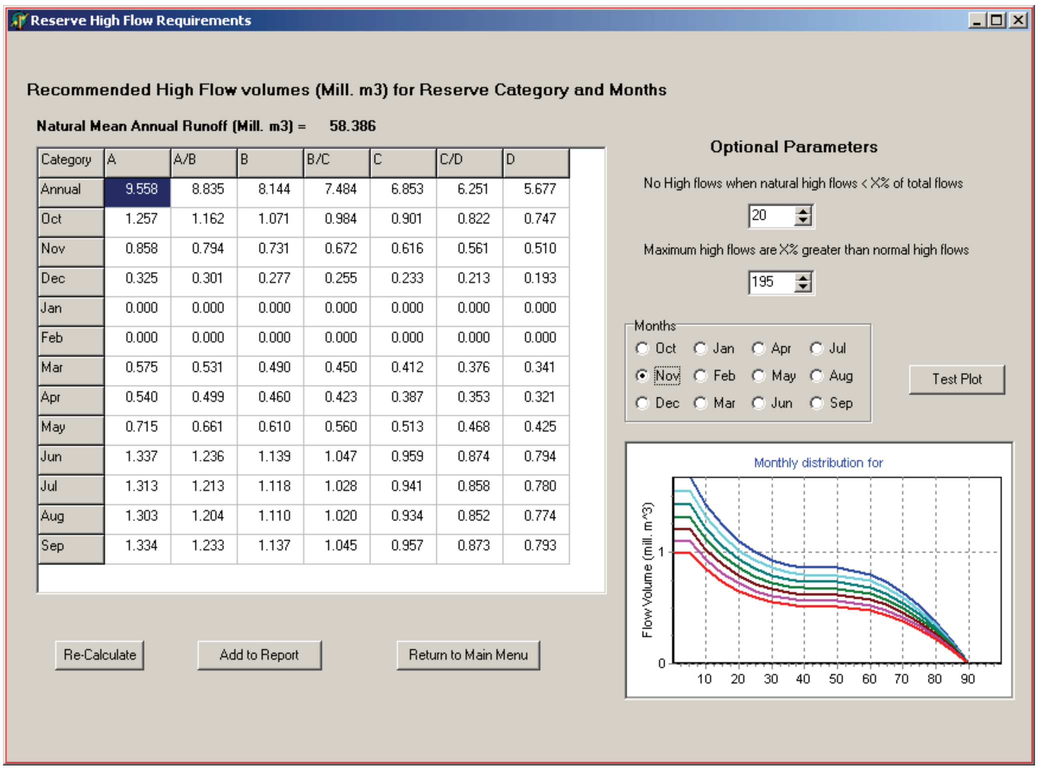
In general terms it is difficult to offer generic guidelines for the use of the options available with the ecological sub-model as almost every river situation will be different. It is possible that further guidelines will emerge as the model is used in practice and these can be documented and added to a later version of the user manual. Most of the current guidelines are related to using the present day stress situation and the PES to guide the user in the selection of options. It is then up to the user to try different options until the patterns of variation in stress appear to be appropriate. The more that a user understands about the river and the differences between the natural and present day conditions, the easier it will be to select appropriate options and generate an acceptable output result.

4.6 DETERMINE FLOOD VOLUMES (THE FLOOD SUB-MODEL)

It was never the intention of this project to include any new ways of dealing with the high flow Reserve requirements, which were always defined with low confidence in the original Desktop model and do not form part of the more detailed Flow-Stressor Response approach. However, a simplified high flow Reserve estimation module has been included for completeness (Figure 4.11). The principle of the approach is to use a method similar to that used in the original Desktop Reserve model to relate the annual high flow requirements to the hydrological index (see the second row of the main table in Figure 4.11). The seasonal distribution of the high flow requirements is based on the percentage of the total flow represented by high flows using the baseflow separations from the hydrology sub-model (see the table given in the lower part of Figure 4.2) at the 50% point on the flow duration curves. If the high flow proportion of natural flows at the 50% point for any month is lower than the limit (default 20%) specified in the relevant selection box of Figure 4.11 (see first selection under the label 'Optional Parameters') then that month is assumed to have no flood requirement. The distribution of the annual requirement over the remaining months is based on the relative values of the high flow proportions at the 50% point. Therefore the month with the lowest relative baseflows (highest proportion of high flows) will be allocated the greatest proportion of the annual high flow requirement.

As with the old Desktop Reserve model, the annual high flow requirement was not expected to occur all of the time and during drier periods lower (or no) high flows would be expected, while in wetter periods, substantially high floods would be expected. In the revised model the 50% point on the duration (or assurance) curve is used for the distributed annual volume estimate and these are reduced using a non-linear curve to the 90% point (see graph at bottom right of Figure 4.11). The highest floods are assumed to occur at the 5% point on the flow duration curve and the volume is determined by a non-linear relationship with frequency (% point value) and a maximum scaling factor that is related to the hydrological variability index (which is also an option that the user can change – see the second selection option under the label 'Optional Parameters' in Figure 4.11).

The other buttons on the high flow screen allow the user to select a specific month and review the plot of requirements for all categories and to add information to an existing report.



Category	A	A/B	B	B/C	C	C/D	D
Annual	9.558	8.835	8.144	7.484	6.853	6.251	5.677
Oct	1.257	1.162	1.071	0.984	0.901	0.822	0.747
Nov	0.858	0.794	0.731	0.672	0.616	0.561	0.510
Dec	0.325	0.301	0.277	0.255	0.233	0.213	0.193
Jan	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Feb	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mar	0.575	0.531	0.490	0.450	0.412	0.376	0.341
Apr	0.540	0.499	0.460	0.423	0.387	0.353	0.321
May	0.715	0.661	0.610	0.560	0.513	0.468	0.425
Jun	1.337	1.236	1.139	1.047	0.959	0.874	0.794
Jul	1.313	1.213	1.118	1.028	0.941	0.858	0.780
Aug	1.303	1.204	1.110	1.020	0.934	0.852	0.774
Sep	1.334	1.233	1.137	1.045	0.957	0.873	0.793

Figure 4.11 The high flow requirement process.

There are two possible user interventions associated with the high flow requirement estimation approach. The first is to set the value for the situation when no high flows will be generated in months when the natural high flows are less than a certain percentage (20% by default) of the total flows. If the user increases this value (and then clicks on 'Re-Calculate') the effects will be seen in the main table. Gradually increasing this value will result in the high flow requirements for some months being removed and the annual value being re-distributed over the other months.

The second option does not affect the main table but the effects will be visible in the graph. This option sets the scale of the maximum high flows (at low frequency of exceedance values). Increasing the percentage value (the default is based on the hydrology data) will change the values of the maximum flood volumes shown in the graph.

It is assumed that in most realistic applications of a desktop approach to setting Reserve requirements the flood requirements will not be applied. Experience suggests that the flood requirements are normally only required in detail when designing the flood release strategies for a major reservoir and the RDRM should not be used for this type of application.

4.7 DETERMINE EWR REQUIREMENTS

This represents the final sub-model of the RDRM and is the module that generates the final results for all ecological categories (Figure 4.12). The screen only includes options for the different displays and at this stage none of the parameters or other options within the total model can be altered to affect the results.

The top left part of the page allows the use to select the month for the display of the flow duration curve (at top right of the screen and includes the natural and present day total flows as well as the selected category assurance line). Immediately below the month selection box is the category selection box that is used for display (all categories are calculated and available in the report). There is also an option to include, or exclude, the high flows from the results displays. These are, however, calculated by default when entering this part of the model and will always form part of the report.

The results are summarized as the flow duration curve plots (top right), time series plots (bottom of the screen) and mean annual volume as million m^3 as well as % MAR. It is important to note that the details of so-called 'maintenance' and 'drought' low flow volumes are not relevant to the RDRM as this is not based on the principles of the BBM (Building Block Methodology). The main output is therefore the long-term mean annual volume requirement and the assurance curves (top right) or rules (part of the report) for each calendar month.

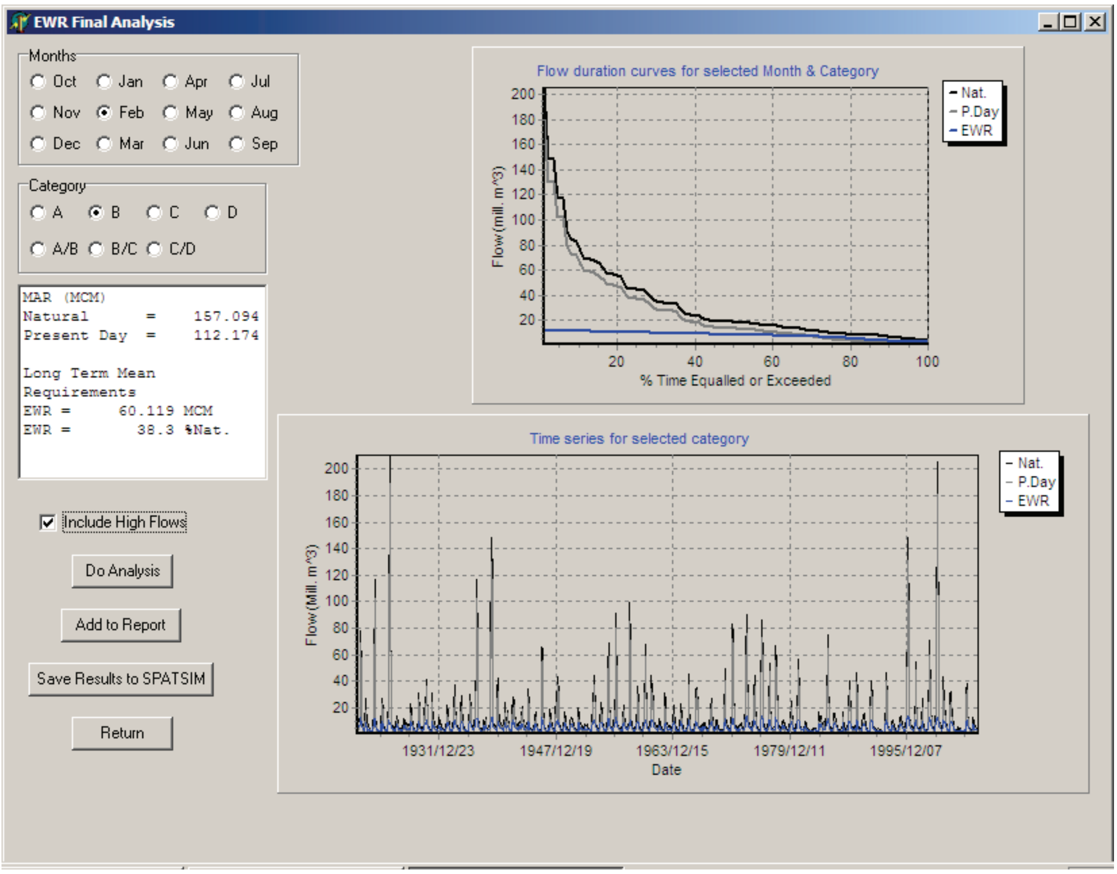


Figure 4.12 The final Reserve analysis and determination screen

The other buttons on this screen allow the user to add the results to the report ('Add to Report') and 'Save Results to SPATSIM'. Figure 4.13 illustrates that the four items of information that can be saved are the total and low flow assurance tables, the time series of Reserve requirements and the analysis report. All of the flow data are saved as million m^3. When the user sets up the model the SPATSIM attributes chosen for the outputs will be related to a specific Reserve category and it is assumed that the same category will be selected when saving the results back to SPATSIM (using the 'Category' selection box at the upper right side of Figure 4.13). If the user wishes to save the results back to SPATSIM for more than a single category, repeated setups of the model must be created, each with a different set of output attributes for the assurance tables and Reserve time series. The model can then be run several times with all the same options chosen except for the final selection of the category used for display and data saving (Figure 4.13). This does not affect the report which includes the results for all categories. The first action after clicking the 'Save Results to SPATSIM' button is a request to confirm that the correct ecological category has been selected.

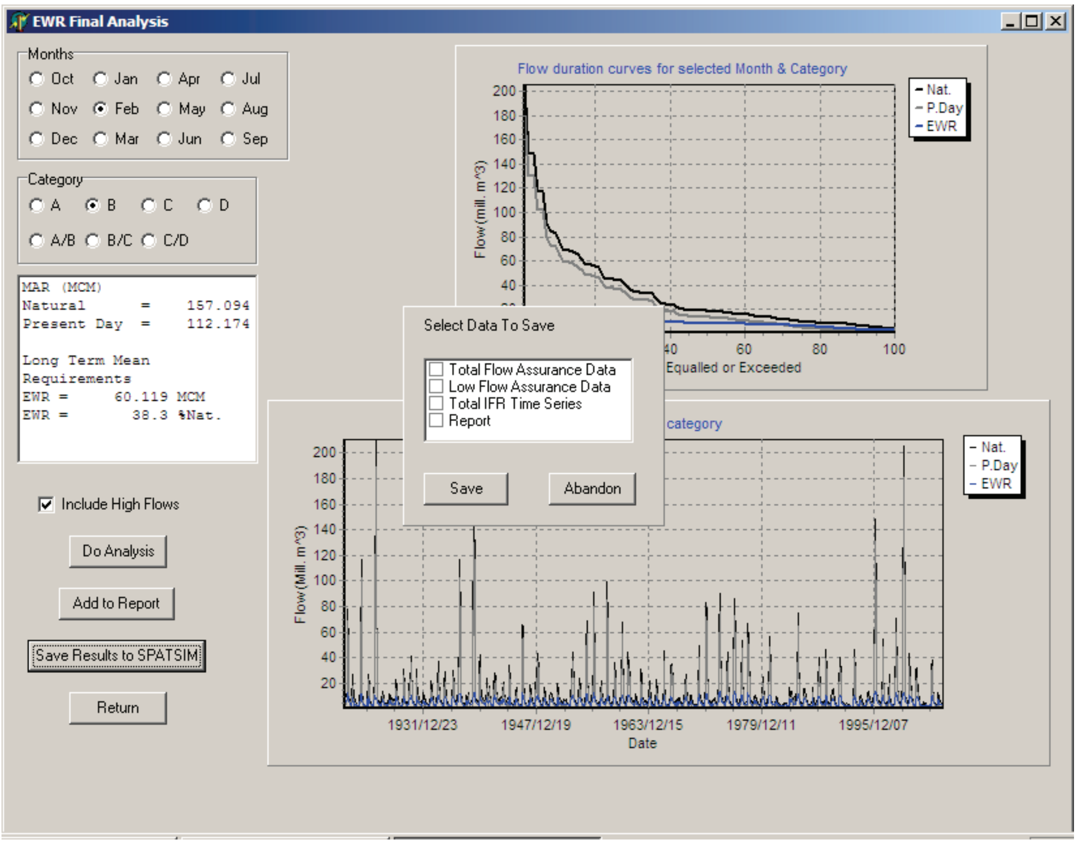


Figure 4.13 The final Reserve analysis and determination screen with the saving data option

4.8 FINAL COMMENTS AND OBSERVATIONS

The successful application of the RDRM can only be achieved if users satisfy three basic requirements before even attempting to use it:

- The first is that they should be familiar with the general functions of SPATSIM (or the updated version SPATSIM-HDSF) and specifically with setting up and running models from SPATSIM (i.e. with the concept of linking information stored within a SPATSIM database to the input and output requirements of a model).
- The second is that the user should be familiar with the general concepts of the Reserve and what it is used within other components of integrated water resources management.
- The third is that the user should be at least generally familiar with the concepts of the Flow-Stressor Response approach used for setting Reserve requirements. Without this background it is likely that the user will become very confused with the outputs and various options associated with the ecological sub-model. Being familiar with the old version of the Desktop Reserve model is not sufficient for the successful use of this model and all potential users are strongly advised to read through the literature and reports that have been written about the FSR approach (see Hughes and Louw, 2010, for example).

It is inevitable that a model of this type can only be considered to be thoroughly tested when it has been used by a number of different people for a wide range of different sites over an extended period of time. It is therefore expected that further changes to both the software and the user guidelines will be necessary in the coming years. The testing that has already been carried out suggests that the model has reached a stage where it can satisfactorily replace the old Desktop Reserve model and that it is acceptable robust in many situations. It should not be assumed that it will generate results that are the same as site specific intermediate or comprehensive Reserve assessments – that is not the purpose of the model and given the uncertainties involved in using desktop level estimates of the channel hydraulic characteristics, this would be impossible anyway.

One of the limitations of the model is that the ecological sub-model and all the flow-stress relationships are based on the three fast habitat classes (Fast Deep, Fast Intermediate and Fast Shallow). The implication is that the model is largely designed for situations where rheophilic (large and/or small) fish are likely to determine the flow requirements. It was not possible to include the requirements for other fish guilds, nor for other biota types (macro-invertebrates or riparian vegetation, for example) during this project, largely because the information on their habitat requirement changes with flow were not available to the project team in a format that matched the design of the model. This may have important implications for rivers where rheophilic fish are not expected to occur under natural conditions and this limitation of the model should be re-visited in the future.

5 ASSESSMENTS OF THE RDRM

The final phase of the project involved setting up applications of the RDRM for a range of sites on different sized rivers (Table 5.1) that had previously been assessed for Reserve requirements. These sites were part of either Rapid, Intermediate or Comprehensive Reserve determinations and the minimum amount of information available was a surveyed channel cross-section and the final Reserve outputs. In many cases, the requirements for the VDG were also available.

Table 5.1 Sites used in the final assessments of the RDRM

River or basin	Site Name	Catchment area (km^2)	Notes
Sabie/MacMac	EWR4	150.0	Part of a comprehensive Reserve determination.
Sabie/Marite	EWR5	476.4	
Sabie/MacMac	X31C_1	54.0	Small rivers extrapolation sites (Rapid level).
Sabie	E9LON	24.0	
Crocodile	E3BLY	76.2	
Karatara	Knysna_4	134.0	Part of an Intermediate Reserve determination.
Kynsna	Knysna_1	30.0	
Caledon	EWRC5	300.0	Part of a comprehensive Reserve determination on tributaries of the Upper Orange River.
Caledon	EWRC6	20490.0	
Kraai	EWRK7	8675.0	
Maputo	JMB4	27378.0	Part of a comprehensive Reserve determination.
Kromme	EWR2	360.0	Part of an Intermediate Reserve determination.
Mokolo	EWR_1A	1633.0	Part of a comprehensive Reserve determination.
Mokolo	JIM	62.0	An small river extrapolation site (Rapid level).
Vaal/Klip	V_EWR6	1710.0	Part of a comprehensive Reserve determination.

The assessments involved checking the following components of the RDRM outputs:

- Whether the maximum baseflow for the wet season month is appropriate and whether a change (and in what direction) to the FDC % point selected would make any difference to any of the other model components and the final outputs.
- Whether the channel cross-section shape is consistent with the surveyed channel cross-section and if not what could be changed to improve the correspondence between the two shapes. Possible changes could be to the geomorphological region or the flood region (and therefore the channel forming discharge used to estimate the maximum channel width).
- Whether the percentage habit availability (across the three fast habitat types: of FS, FI and FD) for the wet season at maximum baseflow is reasonably consistent with the workshop results generated from the FFHA model.
- Where available, the flow requirements at several flow duration curves % points for the wet and dry season were also checked. These were checked with the default settings of the model as well as various other alternatives.
- Finally, the overall outputs from the RDRM were checked against the workshop results (mainly for low flows).

5.1 CHECKING THE MAXIMUM WET SEASON BASEFLOW

Table 5.2 illustrates the effects of changing the FDC % point used to determine the maximum baseflow from the natural baseflow time series. As might be expected the habitat percentages shift slightly in favour of the shallower habitats as the FDC % point is increased and therefore the maximum baseflow reduced. Only in one case (E9LON) did the wet season calendar month change (from February to April when the FDC % point changed from 20% to 40%). The effects on the estimated flow requirements at 95% (droughts) and 60% (moderate flows) for a B ecological categories were quite variable, while the overall effects on the long-term mean baseflow requirement were minor (last column of Table 5.2). This illustrates the robustness of the model and that when the flow requirements are integrated across the whole flow duration curve and for all of the months there are very few changes to the long-term requirement. The long-term requirements predicted by the model were generally very similar to those generated during the previous Reserve requirements, although some significant differences were noted at some sites. These could usually be attributed to some special situations (such as high sediment loads in the Caledon River and generally higher flows being set to compensate for these).

Table 5.2 Effects of changing the FDC% point to determine the maximum baseflow (the last two columns are based on results for B ecological category)

Site & FDC % Point	Wet season baseflow ($m^3 s^{-1}$)	Habit % (FS : FI : FD)	Wet season flows at 95% : 60% FDC ($m^3 s^{-1}$)	Long-term mean EWR (%MAR)
Sabie/Marite EWR5				
10%	7.11	4.8 : 3.9 : 77.6	1.15 : 1.72	29.6
20%	5.47	4.7 : 8.4 : 71.2	1.15 : 1.72	28.7
40%	3.22	11.6 : 22.4 : 48.7	1.17 : 1.82	28.2
Caledon EWRC6				
10%	28.90	0.5 : 1.6 : 38.8	1.85 : 5.74	12.3
20%	22.90	1.2 : 2.6 : 29.3	2.10 : 7.33	12.4
40%	15.50	2.1 : 2.7 : 20.9	2.75 : 8.15	12.5
Sabie E9LON				
10%	0.40	38.8 : 30.4 : 0.0	0.122 : 0.158	41.5
20%	0.36	44.9 : 21.4 : 0.0	0.118 : 0.182	41.7
40%	0.26	45.7 : 11.9 : 0.0	0.130 : 0.166	41.7

Making direct comparisons between the wet season flow requirements at specific FDC % points was found to be quite difficult, largely because it was recognised that the previous Reserve determination studies frequently took into account site specific issues associated with present day conditions, some of which are not flow related. It is clearly understood that these cannot be incorporated into a desktop level determination. In some cases the use of the model facility to align the requirements to the present day stress conditions made a substantial difference and improved the correspondence between the previous results and the model outputs. However, this only occurred where flow related issues dominated the Reserve determinations.

Although the assessments did not produce any conclusive guidelines, there was a tendency for large rivers to require a lower FDC % point (higher maximum baseflow associated with 30% or 40%), while a FDC % point of 10% seemed to be more appropriate for many of the smaller rivers.

5.2 CHANNEL CROSS-SECTION SHAPE

There are two main issues that were assessed for the hydraulics sub-model. The first was the link between the assumed geozone and the measured (or estimated) valley slope, while the second was the selection of the flood region that determines the parameters of the relationship between catchment area and channel forming discharge (and therefore the maximum channel width).

There were several examples amongst the sites assessed where the valley slope was incompatible with the assumed geozone and it was necessary to adjust the zone to match the slope. This appears to be largely a consequence of the relatively coarse scale at which geozones have been defined and the fact that special cases exist where there has been local rejuvenation of the channel or where local geological structure controls have affected the channel size and shape.

There were also situations where the mean annual flood and channel forming discharge values were over-estimated, particularly in large rivers. The data set used by Mkhandi and Kachroo (1997) to generate the regional parameters was very limited and it is not certain that the parameters can be considered applicable to large river basins extending across more than one flood region and with very different flood generating mechanisms throughout the total catchment area. It is therefore recommended that the estimated mean annual flood should be checked for appropriateness against other sources of information related to either the flood values themselves, or the width of the channel. During the assessment it was noted that Google Earth can be used to guide the assessment for large rivers but it is necessary to be careful when measuring channels from Google Earth images. The maximum width used in the RDRM is the total channel width (including possibly vegetated banks) and this is not always easy to identify on the satellite images, particularly where floodplains exist. The alternative is to try and identify the low flow channel (containing water or clear sediment and possibly easier to identify on the images) and check that against the RDRM low flow channel width estimate (that is clearly affected by the estimates of the total channel width and the basic channel shape, which is further related to the geozone selected).

Even if the flood is estimated incorrectly this does not necessarily mean that the final result will be completely wrong. This is because the ecology sub-model results are related to the maximum available habitat at the maximum baseflow – if the channel shape and size changes then so will the maximum available habitat. The default flood region for site EWRK7 is region 9 which suggests a channel forming discharge of some 960 $m^3\ s^{-1}$ and a channel width of over 220 m. The final long-term low flow requirement for a B category is 15.7% MAR. Available hydrological records suggest that the flood should be closer to 400 $m^3\ s^{-1}$ which generates a maximum width of some 120 m (closer to reality according to Google Earth) and the result for the long-term mean low flow requirement is 15.2% – an insignificant change from the previous result with a much larger channel. Despite this result it is still recommended that users make every effort to confirm either the validity of the flood discharge value or the channel dimensions.

5.3 EFFECTS OF INCLUDING DIFFERENT 'PERENNIAL' OR 'ALIGNMENT' OPTIONS

One of the observations during the model assessment workshop (and indeed throughout many previous Reserve determinations) is that site specific considerations that are frequently non-flow related result in seasonal distributions that are very different to the natural situation. The RDRM will never be able to simulate these conditions (unless some manual adjustments are made) as this would violate the general principle upon which the model is based – that the result for any ecological category should be a reflection of the patterns of variation (over different time scales) of the natural flows. However, there are situations where the manual adjustments can lead to substantial differences in pattern between the natural situation (with respect to both stress and flow) and the resulting Reserve. These adjustments are associated with allowing one or more of the critical months Reserve requirements to contain zero flows and the other is to align the requirements to the present day stress conditions. A further option is to use both types of manual adjustment.

Figure 5.1 illustrates the default result for site Kromme EWR2 and the final long-term mean Reserve (B category) for low flows is estimated as 13.5% MAR. If the option to allow the either the dry season to be non-perennial is allowed (All Categories, Wet Season Perennial), or to allow both seasons to be non-perennial the results do not change. However, if these options are retained AND the option to align with present day conditions is used the results are very different. Aligning with D, C and B (Figure 5.2) categories results in low flow Reserves of 9.5%, 8.4% and 6.8% respectively. The Reserve workshop focused on a D category and resulted in a long-term mean for low flows of about 3.5%, while the RDRM for a D category (non-perennial allowed and D category aligned to present day) generated a value of 4.6%.

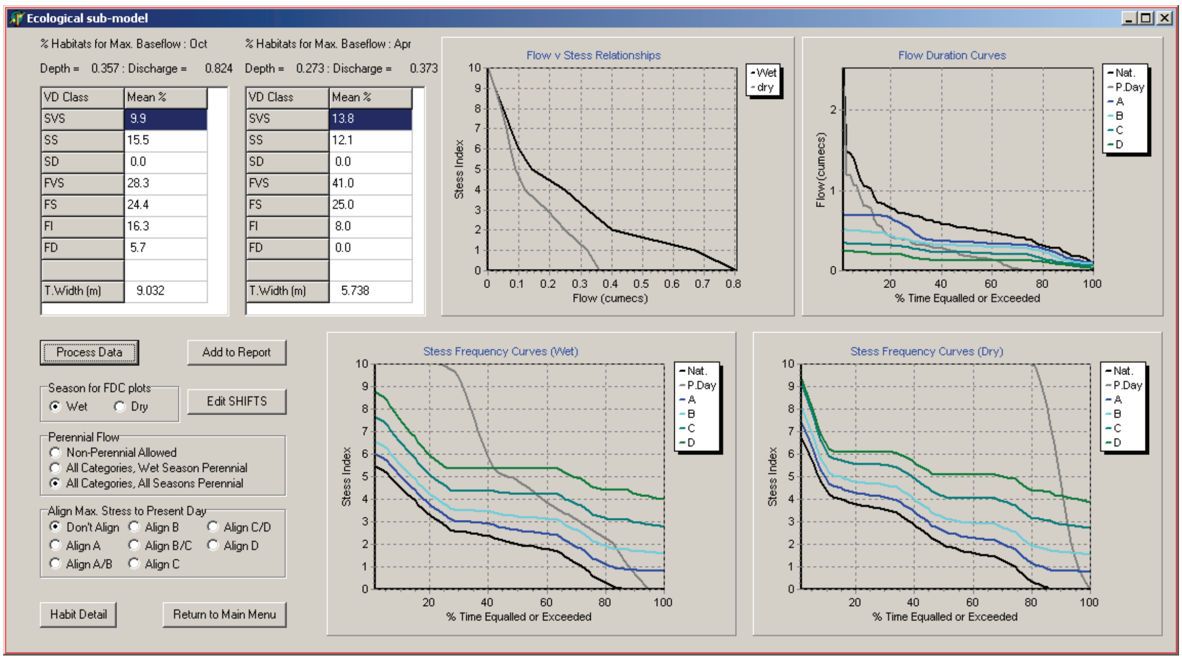


Figure 5.1 Default result for Kromme EWR2

For site Sabie/MacMac EWR4 the long-term mean low flow requirements for B and C categories were 37% and 23% MAR, respectively. The equivalent default results for the RDRM are 36.2% and 27.8% MAR. If the B category drought flows (or maximum stress values) are aligned to present day the results change to 35.4% and 26.4%, while C category drought flows to present day gives values of 37.2% and 29.5%. Clearly there are relatively small changes for this site and while the B category results are all very close to the previously determined Reserve, the RDRM C category results are consistently higher regardless of which option is chosen.

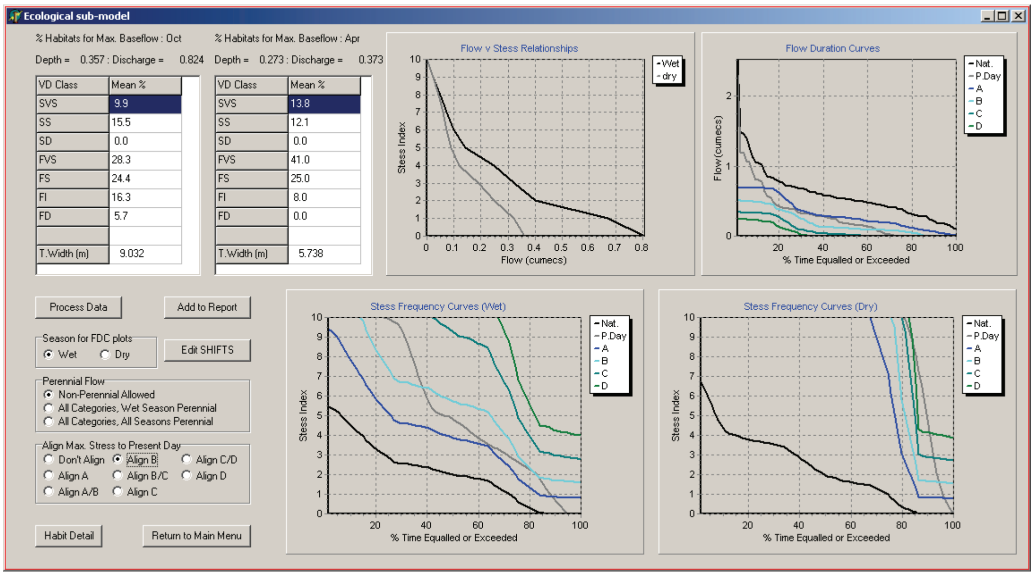


Figure 5.2 Result when aligning a B category with present day and accepting non-perenniality in both seasons.

Table 5.3 illustrates the RDRM results based on comparisons with relatively high confidence Reserve determinations. The results presented are the default model results for the recommended ecological category (REC) as well as some results based on selecting logical options in the model. In this sense 'logical' refers to either tests with alternative FDC % points used to generate the maximum baseflow values, or using one or more of the perenniality and present day condition alignment options. Table 5.3 suggests that improvements can frequently be made by selecting some of these options and that the adjusted results are usually quite close (given the uncertainties of using a desktop model approach) to the more detailed determination results. While it as recognised that Table 3 represents a very limited sample of sites, they do cover a relatively wide range of conditions in terms of climate zone, river size and the degree to which present day flow conditions are different from natural flow conditions.

These results therefore suggest that the model is able to generate sensible low flow Reserve results, despite the limitations of using a desktop approach to generating the hydraulics and an ecological sub-model that also has limitations compared to the much more detailed assessments that form part of normal high confidence Reserve determinations.

There is little doubt that after the Beta version of the model has been used for many more sites modifications to the structure of model will be identified and need to be incorporated.

This issue is almost certainly relevant to the approach used to quantify the high flow requirements which were not tested as part of the assessment undertaken in this project. It is also likely to be relevant to some of the low flow quantification methods, but the conclusion at the end of this project is that the model has reached as stage of development where it can be used with acceptable confidence (albeit much lower than a detailed site specific investigation). No detailed comparisons have been made with the estimates provided by the previous Desktop model as this was not considered appropriate (it is not considered good practice to assess one model against another). However, the general trend of increasing low flow requirements with decreasing degrees of hydrological variability (a major component of the previous Desktop Reserve model) has been retained within the RDRM, although for different reasons and through a different modelling process.

Table 5.3 Previous Reserve determination results and RDRM results for the long-term low flow requirements (all given as %MAR).

River or basin	Site Name	REC category & % MAR	RDRM Default for REC	RDRM Alternative result	Options used to get alternative result
Sabie/MacMac	EWR4	C : 23%	27.8%	26.3%	10% FDC used for Max. Baseflow and C droughts aligned to present day
Sabie/Marite	EWR5	B/C : 22%	25.4%	23.6%	B/C droughts aligned to present day.
Karatara	Knysna_4	B/C : 16%	27.2%	18.4%	Non-perennial allowed in all seasons.
Kynsna	Knysna_1	B : 23%	30.1%	26.9%	10% FDC used for Max. Baseflow.
Caledon	EWRC5	C/D : 15%	9.6%	12.5%	C/D droughts aligned to present day.
Caledon	EWRC6	C : 13%	9.1%	10.0%	30% FDC used for Max. Baseflow.
Kraai	EWRK7	C : 10%	11.8%	10.2%	Non-perennial allowed in all seasons and C droughts aligned to present day.
Maputo	JMB4	C : 19%	26.2%	22.4%	B droughts aligned to present day.
Kromme	EWR2	D : 3%	8.1%	4.6%	Non-perennial allowed in all seasons and D droughts aligned to present day.
Mokolo	EWR_1A	C/D : 13%	16.7%	15.8%	Non-perennial allowed in all seasons and C/D droughts aligned to present day.
Vaal/Klip	V_EWR6	C : 8%	10.9%		No options to improve results.

6 CONCLUSIONS AND RECOMMENDATIONS

The overall conclusion is that the RDRM has reached a stage of development (Beta version) where it can be used by practitioners with some caution. The caution is required to ensure that the model does not generate inappropriate results in situations that have yet to be covered by the assessments undertaken by the project team. These are expected to be rare, but if they do occur it may be necessary to make some structural modifications to the model.

6.1 IDENTIFIED IMPROVEMENTS

The project team have already identified several components of the model that could be improved and would add flexibility to the model. These have not been incorporated at this stage as they involve some extensive modification to the code, which will involve checking to ensure that the existing code generates the same results. There has not been time available during this project to do this and it was considered more important to finalise the Beta version of the model and make it available to potential users. Many of the identified improvements are associated with the use of the model to support Rapid, Intermediate or Comprehensive Reserve determinations where additional information is available that the RDRM will need to use. These improvements are therefore not relevant to the use of the model in a totally desktop environment. However, there is little doubt that the very simplistic high flow requirement component does need to be urgently re-visited, even for a desktop environment.

6.1.1 High flow estimation process

The approach used in detailed Reserve determinations is to identify flood peaks for up to seven (although typically less than 5 are used) different classes that all perform some defined ecological function. These peaks would be converted to volumes by assuming an event duration that is appropriate to the size of the flood peak and the natural hydrological flood regime of the river. The number of each category of event required in each of the months of the year completes the definition of the flood requirements. The flood peaks are related to the channel hydraulics and this provides an opportunity to follow a similar principle within the RDRM.

Some of the existing approaches based on the monthly differences between total flow and separated baseflow could be used to identify the months in which flood requirements are expected. A revision to the model would almost certainly require regional information about the typical frequency of events, duration of events of different magnitudes and the conversion factor from instantaneous peaks to mean daily flow peaks (a measure of catchment response time). It should then be possible to use the hydraulics of the model generated channel cross-section to infer an appropriate range of flood peaks for up to 5 flood classes for each ecological category.

6.1.2 Using a surveyed channel cross-section

Part of the original design concept was to include a facility to replace the randomly generated channel cross-section based on a set of regional parameters and estimation equations with a surveyed channel cross-section. This should be a relatively simple change to make within the model, but it is essential that guidelines are available for the channel survey to ensure that the observed cross-section is compatible with the other parts of the model. Specifically, the channel should be surveyed at least to a point that can accommodate any maximum wet season baseflow that is generated by the hydrology sub-model. If the channel hydraulics are used for high flow estimation in a future version of the model, then the channel survey will have to be complete enough to accommodate much large flows.

Even with a surveyed channel cross-section it will be necessary to define the shape of the relationships between water depth and the Manning's roughness coefficient as well as with the water energy gradient. These are the last 6 values in the hydraulics parameter list shown in Figure 4.5 and are required to calculate the stage-discharge curve and the distribution of hydraulic habitat types at different flow depths. It is expected that the field work associated with a channel survey will include some flow measurements and therefore 1 or 2 points against which the stage-discharge curve can be calibrated by adjusting the values of some of the 6 parameters. Once the surveyed channel cross-section and the stage-discharge curve are established the remainder of the model would remain the same.

6.1.3 Incorporating additional flexibility in the shapes of the stress frequency curves for different ecological categories

While a relatively high degree of flexibility in modifying the shapes of the stress frequency curves has already been built in to the model, especially if the manual adjustment of the 2 'shifts' (Table 4.2) option is used, there is one situation that is not catered for. This situation occurs when the present day flows in one or both seasons are greater than natural flows as a consequence of irrigation releases or return flows. If this situation occurs and is reflected in the difference between the natural and present day flows, it may be appropriate to allow for stress curve shifts that are negative (i.e. decreasing stress as the Ecological Reserve category moves from A to D). It is also possible that there should be a reversal of the shift direction between the seasons. This would occur where wet season flows are used to fill reservoir storage (resulting in reduced flow and increased habitat stress), while dry season flows are enhanced with releases from storage (resulting in increased flows and reduced habitat stress). This type of situation can occur below reservoirs operated for hydro-power generation.

It will be necessary to discuss the ecological consequences of enhanced flows before guidelines can be developed and translated into suitable algorithms to be incorporated into the model.

6.1.4 Invertebrate requirements

During this WRC project, insufficient information was available to adjust the VDG model for use for invertebrates. The ecological component therefore focuses on the suitability of hydraulic habitat in terms of fish requirements only and will have to serve as a surrogate for invertebrate requirements. As there are many systems, such as in the Eastern Cape, with a very low fish diversity, it is essential that the invertebrate component be included during a next phase. It is therefore recommended that, during a next phase of the project, the invertebrate requirements are included in the RDRM.

6.1.5 Fish guilds

The VDG model as is currently in place uses only small and large rheophilic guild requirements as it was identified that it highly likely caters for all other guilds and would provide more conservative answers. More information is becoming available on the occurrence of the different guilds at various locality or river reaches in the country. The most important current project which is relevant in this regard is the WRC project K5/2041: Review and update of the desktop Present Ecological State (PES) and Ecological Importance (EI) – Ecological Sensitivity (ES) of South African rivers according to sub-quaternary catchments. This project will cover thousands of river reaches, and a species list for each reach will be available. This readily available information can be accessed by the non-fish specialist to determine the guild that will occur at the point of interest. This therefore opens up the scope to investigate more detailed requirements for a larger range of fish guilds.

6.2 APPLICATION OF THE MODEL OUTSIDE SOUTH AFRICA

The original Desktop model has been applied in several countries outside South Africa and in each case it has been necessary to develop a set of regional parameters that are appropriate to the conditions existing in those other countries. To a certain extent the same will apply for the RDRM. While the parameter estimation routines used for the hydraulics sub-model have been based on approaches used in many countries there is the possibility that some of the equations will not be appropriate. Certainly the flood regions are specific to South Africa and a new set of regions and equations would be needed for other countries. The use of the Geozones are also quite specific to South Africa and are unlikely to be applicable to a wide range of other countries where the channel forming processes may be different. Similarly, the ecological sub-model is based on South African experience, although the use of the Fast Deep, Intermediate and Shallow habitat types should be transferrable to other counties.

6.3 FUTURE TRAINING REQUIREMENTS FOR THE RDRM

As the model is very different from the Desktop Reserve Model, training in the use and application of this model is essential. The training should take place in sequential order as follows:

- SPATSIM training (to focus on loading of hydrology time series for use in the RDRM)

- Habitat Flow Stressor Response training will also be required to interpret the stress graphs in the RDRM.
- RDRM

This training should also be available for PSPs to ensure the consistent application of the model and the widespread use thereof.

7 REFERENCES

Annable, WK (1996) Database of Morphological of Watercourses in Southern Ontario. Ontario Ministry of Natural Resources

Barnes, HH (1967) Roughness Characteristics of Natural Rivers. U.S Geological Survey Water-Supply Paper 1849, U.S Geological Survey, Washington

Birkhead, AL & Desai, AY (2009) Collation and Synthesis of Hydraulic Information Collected Over the Past Decade in Southern Africa to Inform Environmental Flow Requirements. WRC Project K8/795

Chow VT (1959) Open Channel Hydraulics. McGraw-Hill, New York

DEGANI, G., Herbst, N., Bromley, J., Levanon, D., Netzer, Y., Harari N. and Glazman H. 1993. Relationship between current velocity, depth and the invertebrate community in a stable river system. Hydrobiologia 263 (3). 163-172.

Desai, AY (2007) Guide to Hydraulic Characteristics of South African Rivers. MSc(Eng) project report, University of the Witwatersrand, Johannesburg, South Africa.

FISHBASE (2010) www.fishbase.org

Hicks, DM & Mason, PD (1998) Roughness Characteristics of New Zealand Rivers. National Institute of Water and Atmospheric Research Ltd, New Zealand

Hirschowitz, PM, Birkhead, AL and James, CS (2007) Hydraulic Modelling for Ecological Studies for South African Rivers, Water Research Commission, WRC Report No. 1508/1/07, Pretoria, South Africa 250pp

Hughes, DA & Hannart, P (2003) A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. Journ. Hydrol. **270**(3-4), 167-181.

Hughes, DA & Hannart, P (2003) A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. Journ. Hydrol. 270(3-4), 167-181.

Hughes, DA & Louw, D (2010) Integrating hydrology, hydraulics and ecological response into a flexible approach to the determination of environmental water requirements for rivers. Environ. Model. & Software **25**(8), 910-918.

Hughes, DA (1999) Towards the incorporation of magnitude-frequency concepts into the Building Block Methodology used for quantifying ecological flow requirements of South African rivers. Water SA. **25**(3), 279-284.

Hughes, DA (2005) Hydrological issues associated with the determination of environmental water requirements of ephemeral rivers. *River Research and Applications* **21**(8), 899-908.

Hughes, DA, Hannart, P & Watkins, D (2003) Continuous baseflow separation from time series of daily and monthly streamflow data. Water SA **29**(1), 43-48

Jonker, V & Shand, MJ (2010) Channel Maintenance Flows, In: Ecohydraulics for South African Rivers – A Review and Guide. James, C.S. and King, J.M. (eds), Water Research Commission Report no. TT 453/10, Pretoria, South Africa

King, J & Louw, D (1998) Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. Aquatic Ecosystem Health and Management **1,** 109-124.

Kleynhans CJ (2003) National Aquatic Ecosystem Biomonitoring Programme: Report on a National Workshop on the use of Fish in Aquatic System Health Assessment. NAEBP Report Series No. 16. Institute for Water Quality Studies, DWAF, Pretoria. South Africa.

Kleynhans CJ, Louw MD, Graham M, 2008. Module G: EcoClassification and EcoStatus determination in River EcoClassification: Index of Habitat Integrity (Section 1, Technical manual) Joint Water Research Commission and Department of Water Affairs and Forestry report. WRC Report No. TT 377-08

Kleynhans, C.J. (2008) Developing an approach for assessing site similarity and predicting fish indicator species. In: Principles of a process to estimate and/or extrapolate environmental flow requirements. Report produced for the Water Research Commission, South Africa by Water for Africa (Pty) Ltd.

Lamouroux, N, Souchon, Y & Herouin, E (1995) Predicting Velocity Frequency Distributions in Stream Reaches. Water Res. Res. **31**(9), 2367-2375

Leopold, L.B. and Maddock, T.J. (1953) Hydraulic Geometry of Stream Channels and Some Physiographic Implications, U.S. Geological Survey Professional Paper 252, 55 p.

Mkhandi, S & Kachroo, R (1997) Regional Flood Frequency Analysis for Southern Africa. In: Southern Africa FRIEND, UNESCO IHP-V, Technical Documents in Hydrology, No 15, pp 130-150

Monadjemi, P (1994) General Formulation of Best Hydraulic Channel Section, Journal of Irrigation and Drainage Engineering **120**(1), 27–35

Moolman, J, Dollar, ESJ, & Silberbauer, MJ (2006) Automated Procedures To Determine River Longitudinal Profiles And Valley Widths, unpublished.

Noble, RG & Hemens, J (1978). Inland water systems in South Africa- a review of research needs. South African National Scientific Programmes Report No 34, CSIR, Pretoria.

O'Keeffe, J, Hughes, DA & Tharme, R (2002) Linking ecological responses to altered flows, for use in environmental flow assessments: the Flow Stressor-Response method. Verh. Internat. Verein. Limnol., 28, 84-92.

O'keeffe, J; HugheS DA and Tharme, R., 2002. Linking ecological responses to altered flows, for use in environmental flow assessments: the Flow Stressor-Response method. Verhandlugen International Vereinigung Limnologie 28, 84-92.

Richards, K (1982) Rivers: Form and Process in Alluvial Channels. Methuen, London
Roberts, T. H., and O'Neil, L. J. 1985. Species selection for habitat assessments. Miscellaneous Paper. EL-85-8. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Root, R. B. 1967. The niche exploitation pattern of the blue-gray gnatcatcher. Ecology 37:317-350.

Rowntree, KM & Wadeson, RA (1999) A Hierarchical Geomorphological Model for the Classification of Selected South African Rivers. Water Resource Commission, WRC Report No. 497/1/99, Pretoria, South Africa

Skelton P. H., (2001) A complete guide to freshwater fishes of Southern Africa. Struik Publishers (Pty) Ltd., Cape Town, South Africa. 395pp.

van Rijn, L (1984) Sediment Transport (3 parts). American Society of Civil Engineers, Journal of Hydraulic Engineering: Part I, 110(10), 1431-56; Part II, 110(11), 1613-41; Part III, 110 (12), 1733-54

Welcomme RL, Winemiller KO & Cowx IG (2006). Fish environmental guilds as a tool for assessment of ecological conditions of rivers. River Res. Applic. **22**: 377-396.

Wohl, EE & Wilcox A (2005) Channel Geometry of Mountain Streams in New Zealand. Jour. Hydrol. **300**, 252-266

Yalin, MS (1977) Mechanics of Sediment Transport, 2nd Ed., Pergamon, Oxford.

APPENDIX A: EXAMPLE OUTPUT TEXT FILE FROM THE RDRM

Revised Desktop Model outputs for site: Sabie 5 (EWR5)

HYDROLOGY DATA SUMMARY

Natural Flows:					Present Day Flows:				
Area	MAR	Ann.SD	Q75	Ann.	Area	MAR	Ann.SD	Q75	Ann.
(km^2)	(m^3 * 10^6)			CV	(km^2)	(m^3 * 10^6)			CV
0.00	157.09	102.52	4.10	0.65	0.00	112.17	94.08	1.51	0.84

% Zero flows = 0.0 — % Zero flows = 0.0
Baseflow Parameters: A = 0.960, B = 0.44Baseflow Parameters: A = 0.960, B = 0.440
BFI = 0.44 : Hydro Index = 3.1 — BFI = 0.35 : Hydro Index = 5.2

MONTH	MEAN	SD	CV	MONTH	MEAN	SD	CV
	(m^3 * 10^6)				(m^3 * 10^6)		
Oct	4.15	2.10	0.51	Oct	1.77	1.43	0.81
Nov	8.53	6.59	0.77	Nov	4.36	4.81	1.10
Dec	16.26	14.91	0.92	Dec	9.97	12.30	1.23
Jan	24.32	21.58	0.89	Jan	17.29	19.32	1.12
Feb	33.12	36.71	1.11	Feb	26.46	33.19	1.25
Mar	29.75	34.28	1.15	Mar	24.36	31.46	1.29
Apr	15.42	14.67	0.95	Apr	12.91	15.22	1.18
May	7.68	2.88	0.37	May	5.27	3.11	0.59
Jun	5.59	1.44	0.26	Jun	3.44	1.71	0.50
Jul	4.69	1.34	0.29	Jul	2.74	1.60	0.59
Aug	3.96	1.22	0.31	Aug	1.92	1.22	0.64
Sep	3.63	1.63	0.45	Sep	1.69	1.42	0.84

Critical months: WET : Feb, DRY : Sep
Max. baseflows (m^3/s): WET : 5.474, DRY : 1.666

HYDRAULICS DATA SUMMARY

Geomorph. Zone 4
Flood Zone 4
Max. Channel width (m) 15.10
Max. Channel Depth (m) 2.32
Max. Channel Discharge (m^3/s) between 55.153 and 59.616

FLOW – STRESSOR RESPONSE DATA SUMMARY

Table of initial SHIFT factors for the Stress Frequency Curves

Category	High SHIFT	Low SHIFT
A	0.100	0.100
A/B	0.150	0.150
B	0.200	0.200
B/C	0.300	0.275
C	0.400	0.350
C/D	0.500	0.400
D	0.600	0.500

Perenniality Rules
All Seasons Perennial Forced

Alignment of maximum stress to Present Day stress
Not Aligned

Table of flows ($m^{3/2}$) v stress index

Stress	Wet Season Flow	Dry Season Flow
0	5.474	1.620
1	2.229	1.312
2	1.651	1.058
3	1.229	0.841
4	0.965	0.650
5	0.804	0.542
6	0.643	0.433
7	0.483	0.325
8	0.322	0.217
9	0.161	0.108
10	0.000	0.000

HIGH FLOW ESTIMATION SUMMARY DETAILS

No High flows when natural high flows are <20% of total flows
Maximum high flows are 162% greater than normal high flows

Table of normal high flow requirements (Mill. m^3)

Category	A	A/B	B	B/C	C	C/D	D
Annual	19.209	18.046	16.906	15.790	14.696	13.624	12.574
Oct	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nov	1.622	1.524	1.427	1.333	1.241	1.150	1.062
Dec	3.611	3.392	3.178	2.968	2.763	2.561	2.364
Jan	4.610	4.331	4.057	3.789	3.527	3.269	3.018
Feb	4.403	4.136	3.875	3.619	3.368	3.123	2.882
Mar	3.634	3.414	3.198	2.987	2.780	2.577	2.379
Apr	1.330	1.250	1.171	1.093	1.018	0.943	0.871
May	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Jun	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Jul	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Aug	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sep	0.000	0.000	0.000	0.000	0.000	0.000	0.000

FINAL RESERVE SUMMARY DETAILS

Long term mean flow requirements (Mill. m^3 and %MAR)

Category	Low Flows		Total Flows	
	Mill. m^3	%MAR	Mill. m^3	%MAR
A	52.083	33.2	68.932	43.9
A/B	46.964	29.9	62.793	40.0
B	44.037	28.0	58.866	37.5
B/C	39.648	25.2	53.498	34.1
C	35.663	22.7	48.553	30.9
C/D	32.808	20.9	44.758	28.5
D	28.315	18.0	39.345	25.0

FLOW DURATION and RESERVE ASSURANCE TABLES

Columns are FDC percentage points:

Natural Total flow duration curve (mill. m^3)

	10	20	30	40	50	60	70	80	90	99
Oct	6.630	5.510	4.675	4.200	3.375	3.120	2.875	2.660	2.445	1.825
Nov	16.675	12.580	9.845	7.580	6.315	5.740	4.680	3.460	3.030	2.263
Dec	32.210	23.580	17.255	14.620	11.300	9.660	7.510	6.250	5.190	3.285
Jan	62.790	39.650	25.610	21.090	16.915	12.680	10.545	9.470	6.895	4.708
Feb	78.725	55.230	35.570	23.730	18.500	15.610	11.640	8.570	6.690	3.649
Mar	65.155	43.160	32.290	24.890	18.260	12.490	11.070	8.550	7.145	4.025
Apr	29.010	21.210	17.545	12.380	10.430	9.460	8.305	7.270	6.370	3.624
May	10.860	9.250	8.545	8.120	7.410	6.810	6.295	5.310	4.865	3.026
Jun	7.635	7.010	6.330	5.910	5.615	5.060	4.705	4.210	3.850	2.902
Jul	6.535	5.650	5.195	4.860	4.425	4.220	3.885	3.590	3.345	2.533
Aug	5.465	4.520	4.275	4.000	3.670	3.490	3.280	3.050	2.825	2.162
Sep	5.450	4.340	3.695	3.390	3.215	3.010	2.820	2.620	2.400	1.855

Natural Baseflow flow duration curve (mill. m^3)

	10	20	30	40	50	60	70	80	90	99
Oct	1.819	1.636	1.415	1.213	1.138	1.080	1.006	0.941	0.885	0.681
Nov	2.282	1.952	1.757	1.618	1.446	1.338	1.207	1.084	0.956	0.729
Dec	3.010	2.439	2.201	1.813	1.719	1.603	1.435	1.306	1.168	0.933
Jan	4.591	3.386	2.749	2.427	2.131	1.905	1.705	1.560	1.356	1.038
Feb	7.100	5.236	3.743	3.272	2.693	2.329	2.162	1.878	1.734	1.222
Mar	6.146	4.657	3.733	3.197	2.681	2.380	1.997	1.848	1.601	1.164
Apr	4.767	3.993	3.304	3.034	2.578	2.311	2.026	1.893	1.683	1.214
May	3.439	3.099	2.879	2.479	2.194	1.986	1.836	1.745	1.588	1.114
Jun	2.916	2.658	2.324	2.184	1.950	1.817	1.749	1.582	1.480	1.089
Jul	2.292	2.054	1.897	1.726	1.635	1.564	1.450	1.340	1.243	0.946
Aug	1.958	1.688	1.574	1.493	1.370	1.303	1.225	1.139	1.053	0.807
Sep	1.905	1.597	1.420	1.308	1.240	1.161	1.088	1.011	0.926	0.715

Category Low Flow Assurance curves (mill. m^3)

A Category

	10	20	30	40	50	60	70	80	90	99
Oct	3.455	3.455	3.147	2.782	2.648	2.590	2.497	2.379	2.208	1.825
Nov	4.353	4.242	3.967	3.792	3.422	3.136	2.934	2.705	2.342	2.013
Dec	5.711	5.192	4.907	4.384	4.094	3.832	3.570	3.316	2.917	2.479
Jan	7.407	6.542	5.904	5.457	4.864	4.495	4.182	3.914	3.432	2.913
Feb	8.137	7.571	6.512	6.088	5.201	4.895	4.621	4.195	3.878	2.773
Mar	9.036	8.003	7.533	6.619	5.903	5.549	4.826	4.498	3.982	3.176
Apr	7.502	7.168	6.447	6.149	5.447	5.232	4.760	4.492	4.065	3.241
May	6.354	6.322	6.014	5.542	4.969	4.719	4.465	4.315	3.947	3.114
Jun	5.379	5.363	5.012	4.819	4.388	4.210	4.093	3.834	3.519	2.794
Jul	4.538	4.538	4.365	4.132	3.924	3.776	3.592	3.397	3.072	2.539
Aug	3.935	3.881	3.767	3.654	3.401	3.222	3.095	2.952	2.669	2.271
Sep	3.659	3.622	3.300	3.156	2.987	2.769	2.676	2.583	2.273	1.953

A/B Category

	10	20	30	40	50	60	70	80	90	99
Oct	3.070	3.070	2.809	2.504	2.493	2.453	2.379	2.277	2.126	1.773
Nov	3.954	3.857	3.638	3.508	3.222	2.976	2.804	2.597	2.253	1.958
Dec	5.061	4.606	4.394	4.019	3.855	3.633	3.406	3.178	2.808	2.438
Jan	6.138	5.487	5.090	4.871	4.578	4.255	3.982	3.741	3.305	2.830
Feb	5.584	5.335	5.194	5.167	4.892	4.624	4.386	3.990	3.747	2.690
Mar	6.827	6.268	6.233	5.670	5.555	5.254	4.586	4.288	3.839	3.087
Apr	6.090	5.688	5.350	5.329	5.125	4.946	4.522	4.289	3.921	3.152
May	5.405	5.362	5.161	4.933	4.676	4.465	4.248	4.118	3.805	3.027
Jun	4.722	4.700	4.449	4.359	4.130	3.987	3.897	3.665	3.391	2.714
Jul	4.109	4.108	3.975	3.810	3.695	3.580	3.427	3.254	2.957	2.466
Aug	3.629	3.575	3.485	3.399	3.202	3.058	2.957	2.833	2.567	2.206
Sep	3.391	3.345	3.077	2.957	2.810	2.631	2.559	2.484	2.182	1.885

B Category

Oct	2.843	2.843	2.601	2.347	2.343	2.319	2.262	2.184	2.047	1.709
Nov	3.679	3.580	3.374	3.270	3.034	2.821	2.674	2.491	2.165	1.883
Dec	4.695	4.270	4.070	3.744	3.625	3.437	3.243	3.048	2.701	2.359
Jan	5.630	5.072	4.707	4.528	4.299	4.019	3.784	3.589	3.183	2.732
Feb	4.972	4.888	4.783	4.783	4.584	4.353	4.152	3.839	3.616	2.597
Mar	6.166	5.809	5.752	5.281	5.210	4.961	4.349	4.113	3.701	2.980
Apr	5.574	5.241	4.947	4.943	4.804	4.660	4.286	4.115	3.782	3.041
May	5.006	4.959	4.771	4.585	4.390	4.214	4.033	3.951	3.668	2.918
Jun	4.379	4.355	4.120	4.056	3.881	3.767	3.702	3.516	3.267	2.618
Jul	3.818	3.813	3.684	3.550	3.476	3.388	3.262	3.122	2.846	2.375
Aug	3.384	3.320	3.232	3.169	3.015	2.898	2.819	2.718	2.468	2.122
Sep	3.168	3.106	2.853	2.758	2.650	2.494	2.442	2.385	2.100	1.807

B/C Category

Oct	2.507	2.507	2.303	2.118	2.112	2.108	2.079	2.027	1.904	1.583
Nov	3.272	3.167	3.000	2.937	2.752	2.565	2.455	2.307	2.009	1.740
Dec	4.181	3.768	3.605	3.352	3.279	3.121	2.978	2.827	2.509	2.179
Jan	4.977	4.447	4.145	4.014	3.867	3.642	3.477	3.333	2.962	2.535
Feb	4.290	4.175	4.155	4.155	4.096	3.935	3.821	3.573	3.372	2.403
Mar	5.390	5.077	5.029	4.706	4.667	4.497	3.997	3.826	3.448	2.762
Apr	4.915	4.563	4.340	4.338	4.294	4.214	3.938	3.826	3.525	2.821
May	4.436	4.353	4.198	4.060	3.946	3.817	3.706	3.674	3.418	2.710
Jun	3.873	3.837	3.644	3.613	3.500	3.431	3.402	3.266	3.041	2.428
Jul	3.384	3.372	3.272	3.185	3.147	3.077	2.997	2.895	2.645	2.199
Aug	3.020	2.942	2.878	2.852	2.738	2.636	2.589	2.518	2.291	1.960
Sep	2.833	2.748	2.543	2.491	2.409	2.266	2.243	2.209	1.946	1.664

C Category

Oct	2.216	2.216	2.028	1.940	1.936	1.932	1.910	1.875	1.764	1.483
Nov	2.912	2.810	2.650	2.594	2.464	2.328	2.248	2.132	1.856	1.626
Dec	3.725	3.335	3.176	2.955	2.926	2.836	2.732	2.613	2.323	2.051
Jan	4.405	3.915	3.634	3.518	3.430	3.314	3.197	3.082	2.746	2.376
Feb	3.712	3.605	3.605	3.605	3.605	3.605	3.533	3.306	3.127	2.257
Mar	4.720	4.429	4.385	4.150	4.123	4.101	3.684	3.540	3.199	2.585
Apr	4.340	3.995	3.852	3.851	3.850	3.838	3.632	3.540	3.272	2.639
May	3.944	3.837	3.678	3.558	3.498	3.490	3.412	3.398	3.173	2.543
Jun	3.441	3.392	3.207	3.176	3.144	3.144	3.128	3.020	2.821	2.277
Jul	3.013	2.990	2.888	2.813	2.812	2.796	2.749	2.677	2.449	2.059
Aug	2.701	2.613	2.545	2.522	2.453	2.394	2.371	2.327	2.120	1.836
Sep	2.534	2.442	2.250	2.202	2.170	2.054	2.054	2.050	1.793	1.574

C/D Category

Oct	2.026	2.026	1.851	1.781	1.779	1.776	1.761	1.740	1.645	1.400
Nov	2.682	2.575	2.424	2.375	2.266	2.144	2.075	1.973	1.726	1.537
Dec	3.439	3.053	2.900	2.701	2.682	2.602	2.521	2.422	2.163	1.938
Jan	4.054	3.573	3.307	3.203	3.127	3.029	2.947	2.862	2.561	2.242
Feb	3.380	3.257	3.257	3.257	3.257	3.257	3.257	3.075	2.928	2.139
Mar	4.323	4.020	3.977	3.785	3.773	3.760	3.395	3.293	2.991	2.442
Apr	3.990	3.636	3.496	3.495	3.495	3.486	3.346	3.291	3.059	2.492
May	3.639	3.504	3.346	3.237	3.193	3.193	3.161	3.160	2.964	2.397
Jun	3.173	3.103	2.926	2.897	2.891	2.890	2.884	2.805	2.634	2.149
Jul	2.784	2.739	2.641	2.583	2.583	2.567	2.536	2.481	2.282	1.943
Aug	2.498	2.395	2.329	2.311	2.258	2.208	2.188	2.155	1.973	1.734
Sep	2.344	2.239	2.062	2.019	2.011	1.896	1.896	1.896	1.665	1.484

D Category

Oct	1.693	1.693	1.570	1.567	1.564	1.562	1.559	1.556	1.525	1.319
Nov	2.266	2.156	2.027	1.986	1.913	1.870	1.817	1.754	1.619	1.447
Dec	2.912	2.556	2.424	2.273	2.271	2.245	2.185	2.148	2.015	1.823
Jan	3.419	2.989	2.763	2.675	2.622	2.580	2.531	2.530	2.371	2.112
Feb	2.812	2.716	2.716	2.716	2.716	2.716	2.716	2.716	2.716	2.019
Mar	3.624	3.357	3.319	3.219	3.216	3.213	2.907	2.902	2.749	2.302

Apr	3.362	3.039	2.936	2.935	2.934	2.925	2.899	2.898	2.804	2.349
May	3.079	2.932	2.806	2.806	2.806	2.806	2.806	2.805	2.725	2.256
Jun	2.688	2.598	2.500	2.499	2.498	2.497	2.496	2.495	2.432	2.024
Jul	2.361	2.294	2.219	2.219	2.218	2.217	2.201	2.201	2.123	1.830
Aug	2.119	2.006	1.948	1.933	1.929	1.927	1.915	1.914	1.844	1.631
Sep	1.989	1.873	1.725	1.688	1.688	1.666	1.666	1.666	1.572	1.393

Category Total Flow Assurance curves (mill. m^3)

A Category

Oct	3.455	3.455	3.147	2.782	2.648	2.590	2.497	2.379	2.208	1.825
Nov	6.812	6.398	5.873	5.509	5.044	4.656	4.147	3.415	2.364	2.013
Dec	11.185	9.990	9.150	8.208	7.705	7.217	6.271	4.896	2.966	2.479
Jan	14.396	12.668	11.321	10.338	9.473	8.816	7.631	5.930	3.496	2.913
Feb	14.812	13.422	11.685	10.750	9.603	9.023	7.915	6.122	3.939	2.773
Mar	14.546	12.832	11.803	10.467	9.537	8.956	7.545	6.087	4.032	3.176
Apr	9.519	8.936	8.010	7.558	6.777	6.479	5.755	5.074	4.083	3.241
May	6.354	6.322	6.014	5.542	4.969	4.719	4.465	4.315	3.947	3.114
Jun	5.379	5.363	5.012	4.819	4.388	4.210	4.093	3.834	3.519	2.794
Jul	4.538	4.538	4.365	4.132	3.924	3.776	3.592	3.397	3.072	2.539
Aug	3.935	3.881	3.767	3.654	3.401	3.222	3.095	2.952	2.669	2.271
Sep	3.659	3.622	3.300	3.156	2.987	2.769	2.676	2.583	2.273	1.953

A/B Category

Oct	3.070	3.070	2.809	2.504	2.493	2.453	2.379	2.277	2.126	1.773
Nov	6.264	5.881	5.428	5.122	4.746	4.405	3.944	3.264	2.274	1.958
Dec	10.204	9.114	8.380	7.612	7.247	6.813	5.944	4.662	2.854	2.438
Jan	12.703	11.242	10.179	9.457	8.908	8.315	7.222	5.636	3.365	2.830
Feb	11.855	10.832	10.054	9.548	9.028	8.502	7.481	5.800	3.804	2.690
Mar	12.003	10.805	10.244	9.285	8.969	8.454	7.140	5.781	3.886	3.087
Apr	7.984	7.348	6.819	6.652	6.374	6.117	5.456	4.836	3.938	3.152
May	5.405	5.362	5.161	4.933	4.676	4.465	4.248	4.118	3.805	3.027
Jun	4.722	4.700	4.449	4.359	4.130	3.987	3.897	3.665	3.391	2.714
Jul	4.109	4.108	3.975	3.810	3.695	3.580	3.427	3.254	2.957	2.466
Aug	3.629	3.575	3.485	3.399	3.202	3.058	2.957	2.833	2.567	2.206
Sep	3.391	3.345	3.077	2.957	2.810	2.631	2.559	2.484	2.182	1.885

B Category

Oct	2.843	2.843	2.601	2.347	2.343	2.319	2.262	2.184	2.047	1.709
Nov	5.843	5.476	5.051	4.781	4.461	4.159	3.741	3.116	2.185	1.883
Dec	9.514	8.493	7.804	7.109	6.803	6.417	5.620	4.439	2.745	2.359
Jan	11.781	10.463	9.474	8.825	8.356	7.822	6.819	5.364	3.239	2.732
Feb	10.847	10.038	9.336	8.887	8.458	7.986	7.051	5.534	3.669	2.597
Mar	11.015	10.059	9.510	8.668	8.408	7.959	6.742	5.512	3.745	2.980
Apr	7.349	6.797	6.322	6.183	5.974	5.757	5.161	4.627	3.798	3.041
May	5.006	4.959	4.771	4.585	4.390	4.214	4.033	3.951	3.668	2.918
Jun	4.379	4.355	4.120	4.056	3.881	3.767	3.702	3.516	3.267	2.618
Jul	3.818	3.813	3.684	3.550	3.476	3.388	3.262	3.122	2.846	2.375
Aug	3.384	3.320	3.232	3.169	3.015	2.898	2.819	2.718	2.468	2.122
Sep	3.168	3.106	2.853	2.758	2.650	2.494	2.442	2.385	2.100	1.807

B/C Category

Oct	2.507	2.507	2.303	2.118	2.112	2.108	2.079	2.027	1.904	1.583
Nov	5.293	4.939	4.566	4.349	4.085	3.815	3.453	2.890	2.027	1.740
Dec	8.681	7.712	7.093	6.495	6.246	5.904	5.199	4.125	2.550	2.179
Jan	10.722	9.482	8.597	8.026	7.656	7.194	6.311	4.991	3.014	2.535
Feb	9.777	8.984	8.408	7.988	7.715	7.328	6.529	5.156	3.421	2.403
Mar	9.918	9.047	8.538	7.869	7.654	7.297	6.232	5.133	3.489	2.762
Apr	6.573	6.016	5.624	5.496	5.387	5.239	4.756	4.304	3.540	2.821
May	4.436	4.353	4.198	4.060	3.946	3.817	3.706	3.674	3.418	2.710
Jun	3.873	3.837	3.644	3.613	3.500	3.431	3.402	3.266	3.041	2.428
Jul	3.384	3.372	3.272	3.185	3.147	3.077	2.997	2.895	2.645	2.199
Aug	3.020	2.942	2.878	2.852	2.738	2.636	2.589	2.518	2.291	1.960
Sep	2.833	2.748	2.543	2.491	2.409	2.266	2.243	2.209	1.946	1.664

C Category										
Oct	2.216	2.216	2.028	1.940	1.936	1.932	1.910	1.875	1.764	1.483
Nov	4.793	4.458	4.108	3.908	3.704	3.491	3.177	2.674	1.874	1.626
Dec	7.914	7.006	6.422	5.880	5.688	5.426	4.799	3.821	2.361	2.051
Jan	9.751	8.601	7.778	7.253	6.956	6.620	5.835	4.625	2.795	2.376
Feb	8.819	8.081	7.563	7.172	6.973	6.763	6.053	4.780	3.174	2.257
Mar	8.935	8.123	7.652	7.094	6.903	6.708	5.764	4.756	3.238	2.585
Apr	5.883	5.347	5.047	4.928	4.867	4.792	4.393	3.985	3.286	2.639
May	3.944	3.837	3.678	3.558	3.498	3.490	3.412	3.398	3.173	2.543
Jun	3.441	3.392	3.207	3.176	3.144	3.144	3.128	3.020	2.821	2.277
Jul	3.013	2.990	2.888	2.813	2.812	2.796	2.749	2.677	2.449	2.059
Aug	2.701	2.613	2.545	2.522	2.453	2.394	2.371	2.327	2.120	1.836
Sep	2.534	2.442	2.250	2.202	2.170	2.054	2.054	2.050	1.793	1.574
C/D Category										
Oct	2.026	2.026	1.851	1.781	1.779	1.776	1.761	1.740	1.645	1.400
Nov	4.426	4.103	3.776	3.593	3.416	3.222	2.936	2.476	1.742	1.537
Dec	7.322	6.456	5.909	5.414	5.243	5.003	4.437	3.542	2.199	1.938
Jan	9.011	7.918	7.149	6.665	6.396	6.094	5.393	4.292	2.607	2.242
Feb	8.114	7.407	6.927	6.564	6.380	6.185	5.594	4.441	2.971	2.139
Mar	8.230	7.445	7.005	6.515	6.350	6.176	5.323	4.421	3.026	2.442
Apr	5.421	4.889	4.604	4.494	4.438	4.371	4.051	3.704	3.072	2.492
May	3.639	3.504	3.346	3.237	3.193	3.193	3.161	3.160	2.964	2.397
Jun	3.173	3.103	2.926	2.897	2.891	2.890	2.884	2.805	2.634	2.149
Jul	2.784	2.739	2.641	2.583	2.583	2.567	2.536	2.481	2.282	1.943
Aug	2.498	2.395	2.329	2.311	2.258	2.208	2.188	2.155	1.973	1.734
Sep	2.344	2.239	2.062	2.019	2.011	1.896	1.896	1.896	1.665	1.484
D Category										
Oct	1.693	1.693	1.570	1.567	1.564	1.562	1.559	1.556	1.525	1.319
Nov	3.875	3.567	3.274	3.111	2.975	2.865	2.611	2.218	1.633	1.447
Dec	6.496	5.697	5.202	4.776	4.635	4.461	3.953	3.182	2.048	1.823
Jan	7.994	6.999	6.308	5.871	5.640	5.409	4.789	3.850	2.413	2.112
Feb	7.182	6.547	6.103	5.769	5.598	5.419	4.873	3.977	2.756	2.019
Mar	7.231	6.518	6.114	5.738	5.594	5.443	4.687	3.943	2.781	2.302
Apr	4.682	4.196	3.959	3.857	3.804	3.741	3.550	3.279	2.816	2.349
May	3.079	2.932	2.806	2.806	2.806	2.806	2.806	2.805	2.725	2.256
Jun	2.688	2.598	2.500	2.499	2.498	2.497	2.496	2.495	2.432	2.024
Jul	2.361	2.294	2.219	2.219	2.218	2.217	2.201	2.201	2.123	1.830
Aug	2.119	2.006	1.948	1.933	1.929	1.927	1.915	1.914	1.844	1.631
Sep	1.989	1.873	1.725	1.688	1.688	1.666	1.666	1.666	1.572	1.393