

# **DEVELOPMENT OF A HYDRAULIC SUB-MODEL AS PART OF A DESKTOP ENVIRONMENTAL FLOW ASSESSMENT METHOD**

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by

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## **ABSTRACT**

Countries around the world have been developing ecological policies to protect their water resources and minimise the impacts of development on their river systems. The concept of 'minimum flows' was initially established as a solution but it did not provide sufficient protection as all elements of a flow regime were found to be important for the protection of the river ecosystem. "Environmental flows" were developed to determine these flow regimes to maintain a river in some defined ecological condition. Rapid, initial estimates of the quantity component of environmental flows may be determined using the Desktop Reserve Model in South Africa. However, the Desktop Reserve Model is dependent upon the characteristics of the reference natural hydrology used. The advancements in hydraulic and ecological relationships from the past decade have prompted the development of a Revised Desktop Reserve Model (RDRM) that would incorporate these relationships. The research in this thesis presents the development of the hydraulic sub-model for the RDRM. The hydraulic sub-model was designed to produce a realistic representation of the hydraulic conditions using hydraulic parameters/characteristics from readily available information for any part of South Africa. Hydraulic data from past EWR studies were used to estimate the hydraulic parameters. These estimated hydraulic parameters were used to develop hydraulic estimation relationships and these relationships were developed based on a combination of regression and rule-based procedures. The estimation relationships were incorporated into the hydraulic sub-model of the integrated RDRM and assessments of the hydraulic outputs and EWR results were undertaken to assess the 'applicability' of the hydraulic sub-model. The hydraulic sub-model was assessed to be at a stage where it can satisfactorily be incorporated in the RDRM and that it is adequately robust in many situations.

Recommendations for future work include the refinement of estimation of the channel forming discharge or the use of spatial imagery to check the maximum channel width estimation. It is also proposed that a future version of the hydraulic sub-model could include flow regime change impacts on channel geomorphology and sedimentology so that flow management scenarios can be more effectively assessed.

## **DEDICATION**

I want to thank Allah, my Creator, who has granted me the knowledge, time and health to complete my thesis.

My thesis is dedicated to:

- My loving wife, Amina, who is my pillar of strength, for her love and support and always encouraging me to do my best.
- My three beautiful children, Ibraaheem, Nasreen and Nadirah, who unselfishly allowed me to work on my thesis.
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## LIST OF ABBREVIATIONS AND ACRONYMS

1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
AEHRA	Adapted Ecological Hydraulic Radius Approach
BBM	Building Block Methodology
BFI	Base Flow Index
CASiMiR	Computer Aided Simulation Model for Instream Flow Requirements
CV	Coefficient of Variation
Def	Default
DEM	Digital Elevation Models
DRIFT	Downstream Response to Imposed Flow Transformations
DRM	Desktop Reserve Model
DWA	Department of Water Affairs
EAFR	Ecologically Acceptable Flow Regime
ER	Ecological Reserve
EF	Environmental Flow
EFA	Environmental Flow Assessment
EFR	Environmental Flow Requirement
ELOHA	Ecological Limits of Hydrological Alteration
EPAM	Expert Panel Method
Eqn	Equation
EVHA	Evaluation of Habitat Method
EWR	Ecological Water Requirement
FDC	Flow Duration Curves
FISRWG	Federal Interagency Stream Restoration Working Group
FLOWRESM	Flow Restoration Methodology
FBB	Fast Boulder & Bedrock (Macroinvertebrate Flow Class)
FC	Flow Class
FCS	Fast Coarse Sediment (Macroinvertebrate Flow Class)
FD	Fast Deep (Fish Flow Class)

FFS	Fast Fine Sediment (Macroinvertebrate Flow Class)
FS	Fast Shallow (Fish Flow Class)
FI	Fast Intermediate (Fish Flow Class)
FvS	Fast very Shallow (Fish Flow Class)
FS-R	Flow Stressor-Response
Geo Zone	Geomorphological Zone
GIS	Geographic Information System
GVF	Gradually Varied Flow
HABFLO	Habitat-Flow Simulation Model
HEC-RAS	Hydrological Engineering Centre's – River Analysis System
HFS-R	Habitat Flow Stressor-Response
HSC	Habitat Suitability Criteria
HV	Habitat Value
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
IHA	Indicators of Hydrological Alteration
LIFE	Lotic Invertebrate Index for Flow Evaluation
MCM	Million Cubic Meters
MVEG	Marginal Vegetation (Macroinvertebrate Flow Class)
NGI	National Geo-spatial Information
nMAR	Natural Mean Annual Runoff
NWA	South African National Water Act (No 36 of 1998)
PHABSIM	Physical Habitat Simulation Model
PUB	Prediction in Ungauged Basins
Rat	Rating Relationship – HABFLO output
RCHARC	Riverine Community Habitat Assessment and Restoration Concept
RDRM	Revised Desktop Reserve Model
Resist	Resistance Relationship – HABFLO output
RHABSIM	Riverine Habitat Simulation Program
RHYHABSIM	River Hydraulics and Habitat Simulation Program
REC	Recommended Ecological Category
RSS	River System Simulator

RVA	Range of Variability Approach
RVF	Rapidly Varied Flow
SA	South Africa
SBB	Slow Boulder & Bedrock (Macroinvertebrate Flow Class)
SCS	Slow Coarse Sediment (Macroinvertebrate Flow Class)
SCS	Soil Conservation Services
SD	Slow Deep (Fish Flow Class)
SPAM	Scientific Panel Assessment Method
SPATSIM	Spatial and Time Series Information Modelling
SPATSIM-HDSF	Spatial and Time Series Information Modelling – Hydrological Decision Support Framework
SRTM	Shuttle Radar Topography Mission
SS	Slow Shallow (Fish Flow Class)
SvS	Slow very Shallow (Fish Flow Class)
UK	United Kingdom
USA	United States of America
VFBB	Very Fast Boulder & Bedrock (Macroinvertebrate Flow Class)
VFCS	Very Fast Coarse Sediment (Macroinvertebrate Flow Class)
VFFS	Very Fast Fine Sediment (Macroinvertebrate Flow Class)
VS	Valley Slope
VSBB	Very Slow Boulder & Bedrock (Macroinvertebrate Flow Class)
VSCS	Very Slow Coarse Sediment (Macroinvertebrate Flow Class)
WUA	Weighted Usable Area
WR90	Surface Water Resources of South Africa 1990
WR2005	Surface Water Resources of South Africa 2005
WRC	Water Research Commission
XS	Cross-sectional

## NOMENCLATURE

### CONSTANTS

$a, b$ and $c$	Coefficients in Equations 2-6 and 2-9
$a, c, k$	Scale factors in Equations 2-7 and 2-8
$b, f, m$	Exponents in Equations 2-7 and 2-8
$x, y$	Coefficients in Equation 2-10
$C_w, P_w$	Coefficients in Equation 6-2
$q, r$	Coefficients in Equation 6-3
$s, t$	Coefficients in Equation 6-4
$C_n, P_n$	Coefficients in Equation 6-7
$C$	Chézy resistance coefficient ( $m^{1/2} s^{-1}$ )
$CA$	Catchment area ( $km^2$ )
$D_s$	Sediment size (mm)
DA	Drainage area ( $mile^2$ )
$f$	Darcy-Weisbach resistance coefficient ( $s m^{-1/3}$ )
$hydro\_var$	Hydrological variability
Macro	Macro roughness
Micro	Micro roughness
P	Wetted perimeter (m)
$g$	Gravitational acceleration ( $m s^{-2}$ )
$k_s$	Nikuradse roughness (m)
k	Dominant roughness (m) – Lamouroux <i>et al.</i> (1995)
M	Median particle size of the bed material (mm)
$n$	Manning's resistance coefficient ( $s m^{-1/3}$ )
$n_c$	Manning's resistance coefficient for channel forming conditions
$n(0)$	Manning's resistance coefficient at zero flow – HABFLO output
$n_{MAX}$	Maximum (low flow) Manning's coefficient
$n_{MIN}$	Minimum (high flow) Manning's coefficient
$n_{VAR}$	Manning's coefficient variability factor
$Q$	Discharge ( $m^3 s^{-1}$ )

$Q_c$	Channel forming discharge ( $\text{m}^3 \text{s}^{-1}$ )
$\bar{Q}$	Mean annual flood ( $\text{m}^3 \text{s}^{-1}$ )
$Q_{10}$	Discharge associated with a return period of 10 years
$Q-y$	Discharge-depth relationship used – HABFLO output
$R$	Hydraulic radius (m)
$Re_*$	Shear Reynolds Number or Boundary Reynolds Number
$R^2$	Coefficient of determination
$S$	Gradient
$S$	Energy gradient – HABFLO output
$S_o$	Bed gradient
$S_f$	Energy gradient
$S_{MAX}$	Maximum (low flow) gradient
$S_{MIN}$	Minimum (high flow) gradient
$S_{VAR}$	Gradient variability factor
$u_*$	Shear velocity
$V$	Uniform velocity or cross-sectional average velocity ( $\text{m s}^{-1}$ )
$Vel_{1m}$	Velocity at flow depth of 1m ( $\text{cm s}^{-1}$ )
$W$	Channel Width or inundated width (m)
$W_{MAX}$	Maximum Channel Width
$y$	Flow depth or stage (m)
$y_{av}$	Average flow depth (m)
$Y_{MAX}$	Maximum flow depth (m)

### GREEK SYMBOLS

$\gamma$	Specific weight of the fluid ( $\text{kg m}^{-2} \text{s}^{-2}$ )
$\mu$	Coefficient of absolute viscosity of a fluid ( $\text{N s m}^{-2}$ or $\text{kg m}^{-1} \text{s}$ )
$\tau_o$	Boundary shear stress ( $\text{N m}^{-2}$ )

## GLOSSARY OF TERMS

Alluvial Channel	A channel formed within the sediment (alluvium) that it transports.
Alluvial / Sedimentary Bars	Morphological feature formed by alluvial deposits within the river bed.
Assurance	Percentage of time at which a flow is equalled or exceeded.
Bankfull discharge	Discharge which fills up the main channel, with further increase in discharge resulting in overflow onto the floodplain.
Bed Forms	The recognised geometries of mobile channel beds as deformed by flowing water.
Biotope	Also Hydraulic biotope – spatial unit in a classification of geomorphological features of a river. Hydraulic biotopes are at the finest scale of the geomorphological classification of rivers and refer to small areas (1-10 m <sup>2</sup> ) characterised by specific water flow characteristics and substratum conditions.
Boundary	Also River bed.
Channel Types	Broad river channel classification – two types are described bedrock channels and alluvial channels.
Community	Populations of different species inhabiting the same geographical area that are linked by mutually dependent interactions.
Comprehensive	Ecological Reserve level associated with highest confidence.
Confidence	Description of uncertainty.
Discharge	The volumetric flow rate in a channel, quantified in m <sup>3</sup> s <sup>-1</sup> .
Diversity	The variety of species in a sample, community, or area, including both the number or richness of species and the degree to which any species are numerically dominant.
Drag	The force exerted on an object by flow around it, arising from surface resistance and the unsymmetrical pressure distribution resulting from flow separation.
Ecohydraulics	Study of the linkages between physical processes and aquatic ecosystems (Centre for Ecohydraulic Research, 2011).
Ecology	The study of the inter-relationships between organisms and their environment and each other.
Ecological Reserve	Defined in the NWA - The quantity and quality of water required to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource.
Ecological Reserve Category	A category indicating the potential management target for the river. Values range from Category A (unmodified, natural) to Category D (largely modified).
Eco-status	An overall assessment of the Ecological Category (A-F), based on a subjective integration of specialist indices (water quality, fish etc).
Effective Discharge	The value of discharge associated with most of the bed material transport in a river, and therefore associated with its morphological characteristics.

Environmental Flow	Commonly used to refer to the flow regime designed to maintain a river in some agreed ecological condition and is seen as a compromise between river basin development and maintenance of the river ecology (Smakhtin, 2007).
Equifinality	Equifinality has a long history in geomorphology, indicating that similar landforms might arise as a result of quite different sets of processes and histories and, without any additional evidence, it might be difficult to identify the particular set of causes or to differentiate different feasible causes from the landform alone (Beven, 2006).
Floodplain	Wetland inundated when a river overtops its banks during flood events resulting in the wetland soils being saturated for extended periods of time.
Flow Class	Habitat preference for biota associated with a combination of hydraulic variables (e.g. depth and velocity) as well as substrate, vegetation and cover for fish and macroinvertebrates.
Flow regime	The timing, magnitude, frequency and duration of different magnitude flows over periods from hours to decades.
Form Resistance	Flow resistance arising from the effects of bed or channel form; associated predominantly with drag forces arising from flow separation and the consequent pressure distribution around objects or channel irregularities.
Freshes	Small flow pulse.
Froude Number	A dimensionless number characterizing the effects of gravity on flow conditions, and hence used to distinguish between subcritical and supercritical flows.
Geomorphological Zone	Classification of South African rivers based on regional slope from 1: 50 000 topographical maps.
Habitat	The combination of all the environmental conditions and all the resources in an area that result in the presence, survival and reproduction of a species in that area.
High flow	Refers to the peaks in the daily hydrograph, determined graphically from daily time series of flows (cf low flows).
Hydraulics	The branch of science and technology concerned with the mechanics of fluids, especially liquids.
Hydraulic Radius	The ratio of the cross-sectional flow area of a channel to its wetted perimeter. It is often approximated by the flow depth for wide, shallow channels.
Hydrology	The study of the inter-relationships and interactions between water and its environment in the hydrological cycle.
Intermediate	Ecological Reserve level associated with highest confidence
Look-up Table	Output from the ecohydraulic model, HABFLO, relating discharge to ecologically relevant hydraulic parameters.
Low Flow	The component/s of the daily hydrograph between high flows, determined graphically from daily time series of flows. It is the low flow component of the flow regime and has a similar meaning to base flows, i.e., it excludes events (floods) (cf high flows).

Macroinvertebrates	Animals without backbones and large enough to be seen with the naked eye.
Nikuradse roughness	A boundary roughness height used for calibration of resistance equations; it is related to, but not equal to, the physical height of roughness elements.
Non-uniform flow	Flow with hydraulic characteristics that vary in space ( <i>cf.</i> 'Uniform flow').
Quaternary	Catchment delineation used as a standard water management unit within South Africa.
Rapid	Ecological Reserve level associated with low confidence.
Rating relationship	See 'Stage-discharge relationship'.
Reserve	The quantity and quality of water required (a) to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997 (Act No. 108 of 1997), for people who are now or who will, in the reasonably near future, be (i) relying upon; (ii) taking water from; or (iii) being supplied from, the relevant water resource; and (b) to protect aquatic ecosystems under the National Water Act, 1998 (Act No. 36 of 1998) in order to secure ecologically sustainable development and use of the relevant water resource. The Reserve refers to the modified EWR, where operational limitations and stakeholder consultation are taken into account.
Resistance, Flow resistance	The effect of the physical characteristics of a conduit on the relationship between discharge, flow depth and velocity.
Resistance coefficient	An empirical coefficient in a resistance equation that accounts for the resistance effects of channel characteristics and energy-dissipating processes at higher resolution than described by the equation.
Reynolds Number	A dimensionless number characterizing the effects of fluid viscosity on flow conditions. Calculated for channels as $Re = 4VR/\nu$ , where $V$ is the average velocity, $R$ is the hydraulic radius and $\nu$ is the kinematic viscosity of the fluid.
Rheophilic	Affiliated with flowing water.
Riparian Vegetation	Riparian vegetation is the narrow band of vegetation within the riparian zone directly adjacent to surface water at base flows.
Riparian Zone	Riparian zones are plant communities contiguous to and affected by surface and subsurface hydrological features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, and drainage ways). Riparian zones have one or both of the following characteristics: distinctly different vegetative species than adjacent areas, and species similar to adjacent areas but exhibiting more vigorous or robust growth forms. Riparian areas are usually transitional between wetland and upland (FISRWG, 1998).
Roughness	The physical size of the roughness elements in a channel; sometimes inappropriately used for a resistance coefficient.
Shear Reynolds Number	A dimensionless number characterizing the effects of boundary roughness and near-bed flow conditions on flow characteristics.
Shear Velocity	A measure of the extent of channel meandering; calculated as the

	distance between two points in the channel measured along the channel divided by the straight-line distance between the two points.
Stage	The height of the water surface above a selected datum; equal to the flow depth if the datum is selected as the lowest point of the channel bed.
Stage-discharge relationship	(Also rating relationship.) A relationship, either graphical or mathematical, that describes the variation of water level with discharge in a channel.
Steady flow	Flow where hydraulic characteristics do not vary with time. The definition is usually loosely applied to ignore turbulent fluctuations.
Stress (HFS-R model)	Index of ecological habitat availability.
Submerged Vegetation	Vegetation with plants totally below the water surface.
Substrate	Generally, a substance that underlies another or on which processes take place. Here it represents the material constituting the river bed. Ecologists use 'substratum' synonymously.
Surface resistance	Flow resistance arising from the effect of boundary shear stress.
Site	Location within a river reach that is ecologically sensitive.
Target Species	The species under examination in a study.
Taxa (singular Taxon)	A definite unit in the classification of plants and animals: a taxonomic unit.
Uniform flow	Flow where hydraulic characteristics are the same at all locations. The definition is usually used loosely to imply constancy between cross sections; it is rarely applied rigorously, as it is an ideal condition that rarely occurs.
Unsteady flow	Flow where hydraulic conditions vary with time ( <i>cf.</i> 'Steady flow').
Wetted Perimeter	The length of channel cross section in contact with water.
WR90	Surface Water Resources of South Africa publications (Midgely <i>et al.</i> , 1994)
WR2005	Water Resources of South Africa publications, 2005 Study, (Middleton and Bailey, 2008)

# 1 INTRODUCTION

## 1.1 Environmental Flows

River systems are used by mankind as sources of water, irrigation, food, energy, waste disposal, industry, recreation, transportation, and self-purification for the economic and social development of a nation. However, the fear of floods and droughts, concerns for food and energy security, and the priority to advance 'limitless economies' (Thomas, 1956) drove water resources developments in countries across the world to implement 'control by construction' solutions (Petts, 2009) to overcome water shortages, prevent floods or increase energy supply (e.g. major dams, major abstractions, hydropower schemes, interbasin transfers). Globally, the natural services provided by river ecosystems are threatened and in some specific cases, are already over-exploited (Postel and Carpenter, 1997; Naiman *et al.*, 2002). Anthropogenic activities have resulted in changes in the natural flow regimes of river systems which then have negative impacts on the aquatic biota and ecological processes. Increasing human demands and uncertainties in the face of climate change (i.e. increases in carbon dioxide concentrations, rising surface temperatures and more extreme precipitation and drought events) have led to additional water resources developments and thus further degradation of rivers and other aquatic ecosystems.

In order to minimise the impacts on river systems, many developed nations began implementing policies to protect their water resources. In the United Kingdom (UK), legislation towards the end of the 19<sup>th</sup> century made provisions for flows below dams, taking account of navigation, public health, the rights of downstream users and the protection of fisheries (Sheail, 1984, 1988). The Water Resources Act of 1963 required River Authorities to set 'minimum acceptable flows'. In the United States of America (USA), The National Environmental Policy Act of 1969 was established to promote the enhancement of the environment and to "encourage productive and enjoyable harmony between man and his environment, prevent or eliminate damage to the environment and biosphere, and stimulate the health and welfare of man and enrich the understanding of the ecological systems and natural resources".

Petts and Maddock (1994) referred to the papers of Phillipson (1954), Wickett (1954) and Ambühl (1959) as three of the earliest contributions that emphasised the importance of flow as an ecological factor. Quantitative and process-based research on rivers was founded during the 1950s and 1960s with a number of early works establishing relationships between flow (Fraser, 1972) and current velocity (Statzner *et al.*, 1988) and salmonid fish, macroinvertebrates and macrophytes (Petts and Maddock, 1994).

The concept of 'minimum flows' was initially established as a solution and was based on the idea that all river health problems are associated with low flows and that as long as the flow is kept at or above a critical level, the river ecosystem will be conserved (Acreman and Dunbar, 2004). However, it has been recognised that minimum flows do not provide sufficient protection for river ecosystems (Petts, 2007) and that all elements of a flow regime, including floods, medium and low flows are important (Poff *et al.*, 1997; Hill and Beschta, 1991; Junk *et al.*, 1989). This has led to the determination of Environmental Flows (EF) for river ecosystems. The term "Environmental Flow" is commonly used to refer to the flow regime designed to maintain a river in some defined ecological condition and is seen as a compromise between river basin development and maintenance of the river ecology (Smakhtin, 2007).

## **1.2 Environmental Flows in South Africa**

South Africa (SA) began to address the problem of trying to meet the increasing human demand for water while minimising the degradation of rivers and other aquatic ecosystems in the 1980s. A realisation had developed for the need to allocate "water for nature" in the country's rivers (Roberts, 1983). The South African National Water Act (NWA) of 1998 (Republic of South Africa, 1998) stipulates that future water resources developments should be environmentally sustainable and that a component of the natural flow of rivers should be reserved to ensure some level of ecological functioning (Hughes & Hannart, 2003). Two types of Reserves are mentioned in the NWA and are referred to as the 'Basic Human Needs Reserve' and the 'Ecological Reserve'. The Basic Human Needs Reserve provides for the essential requirements of individuals served by the water resources and includes water for drinking, food preparation, and personal hygiene. The Ecological Reserve (ER) relates to the

water required to protect aquatic ecosystems of the water resource either by maintaining the river in a certain state (the ecological state or eco-status) or limiting the risk of irreversible ecosystem damage to a given level.

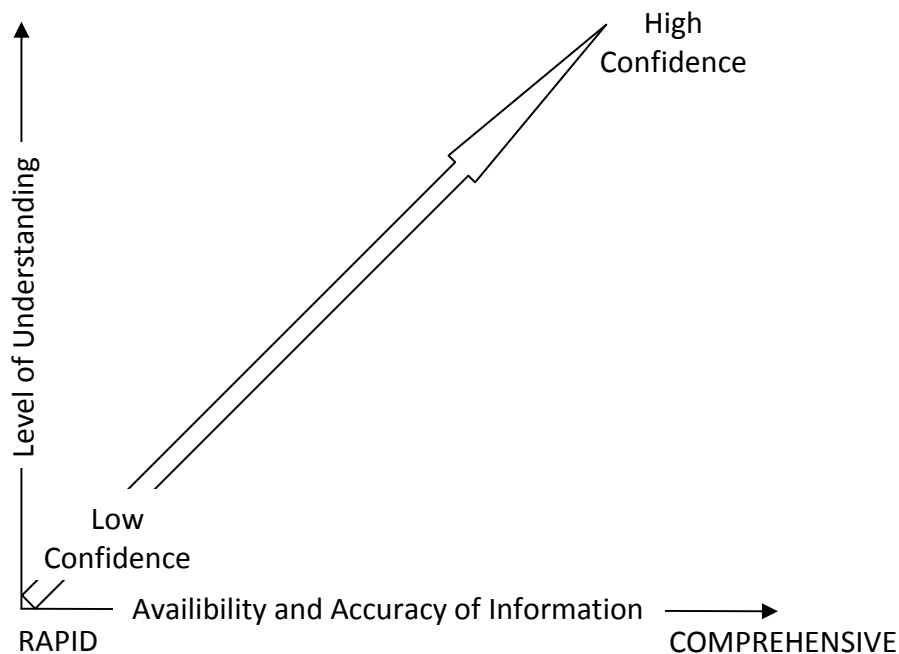
Quantifying the ER for rivers involves determining the water quantity and quality requirements that will ensure that they are sustained in a pre-determined condition (Hughes & Hannart, 2003). The major difference between South African ER and international requirements stems from the objectives of the policies and legislation supporting it. The South African ER aims to maintain a diverse ecosystem through a vision of equity, efficiency and sustainability in the allocation and use of river resources (van Wyk *et al.*, 2006) with the NWA recognising the central role of ecosystems in water supply and therefore gives priority of water to aquatic ecosystems once basic human needs are met (Acreman and Dunbar, 2004). Internationally, the aims of EF studies are to assess the flow requirements of target species and to recommend flows needed to assure maintenance of the population (Stalnaker *et al.*, 1994).

Originally, the requirements (i.e. modified hydrological regimes) for the assessment of ERs were termed Instream Flow Requirements (IFR). However, this term is no longer used as it implies that only the instream component is considered and that riparian zones are excluded. Presently, Environmental Flow Requirement (EFR) is used internationally but Ecological Water Requirement (EWR) is the preferred terminology in SA because the word “flow” is deemed to disregard water quality considerations and, secondly, “ecological” refers specifically to the component of the environment and excludes social aspects (Birkhead, 2010). Based upon the holistic EF assessment method (discussed later in Chapter 2, Section 2.1), three factors are used to determine the EWR of a river; (i) the site specific ecological functioning, (ii) the relationships between flow and habitat that are determined by the hydraulic characteristics of the channel and (iii) the hydrological regime characteristics (Hughes & Hannart, 2003).

The whole length of the river cannot be sampled and assessed. Therefore the process of setting ER for a river is based on representative or critical sites along the river. The critical

sites are selected such that they potentially provide the greatest range of the environmental conditions characteristic of the river reach it represents.

Recognising the financial and time resource constraints associated with implementing a new national policy, SA has accepted the principle that the ERs may be determined at three different levels referred to as Rapid (consisting of Rapid I, II & III), Intermediate and Comprehensive. The levels, as the names indicate, are associated with different degrees of effort (time and cost), different levels of confidence and complexity of the analysis tools used. Confidences are used in ERs to indicate the expected quality and reliability of the results produced. The level of confidence depends firstly on the availability and accuracy of the input information and secondly on the level of understanding (Kleynhans *et al.*, 2005), with the availability and accuracy of information generally increasing with the level of ER. The main difference between the Rapid III (the Rapid level requiring hydraulic information), Intermediate and Comprehensive assessments is in the amount of measured hydraulic data that can be obtained (Jordanova *et al.*, 2002) given the time and cost constraints. Figure 1-1 illustrates the general levels of confidence that can be achieved with the different levels of information (i.e. ER level) and understanding.



**Figure 1-1 Confidences for Ecological Reserves based upon the Availability and Accuracy of Information and the Level of Understanding**

However, as preparations were made for the implementation of the NWA, it became apparent that more rapid methods of assessment in unmeasured catchments were required that could be used for initial planning (Hughes & Hannart, 2003) as it was considered impractical and beyond the available resources to obtain Rapid III, Intermediate or Comprehensive EWR information at all locations of interest. In a similar context, the Prediction in Ungauged Basins (PUB, Sivapalan *et al.*, 2003) initiative was launched in 2003 by the International Association of Hydrological Science with the aim of encouraging a shift in the methods used to predict streamflow, sediment and water-quality variables. The shift should be away from a reliance on calibration-based approaches and towards new techniques based primarily on improved understanding and representations of physical processes. The reason for this was related to the emerging realisation that calibration-based approaches can not be relied upon to generate acceptable results in ungauged basins and the fact that future environmental (including climate) changes suggest that future flow patterns at currently gauged sites are likely to be non-stationary. The need for rapid assessments in ungauged catchments and the development of the Desktop Reserve Model (DRM) (Hughes and Münster, 2000; Hughes and Hannart, 2003) can be seen as a component of PUB in the context of establishing EFs. The DRM provides a method for generating quick, initial estimates of the quantity component of the ER for rivers in SA.

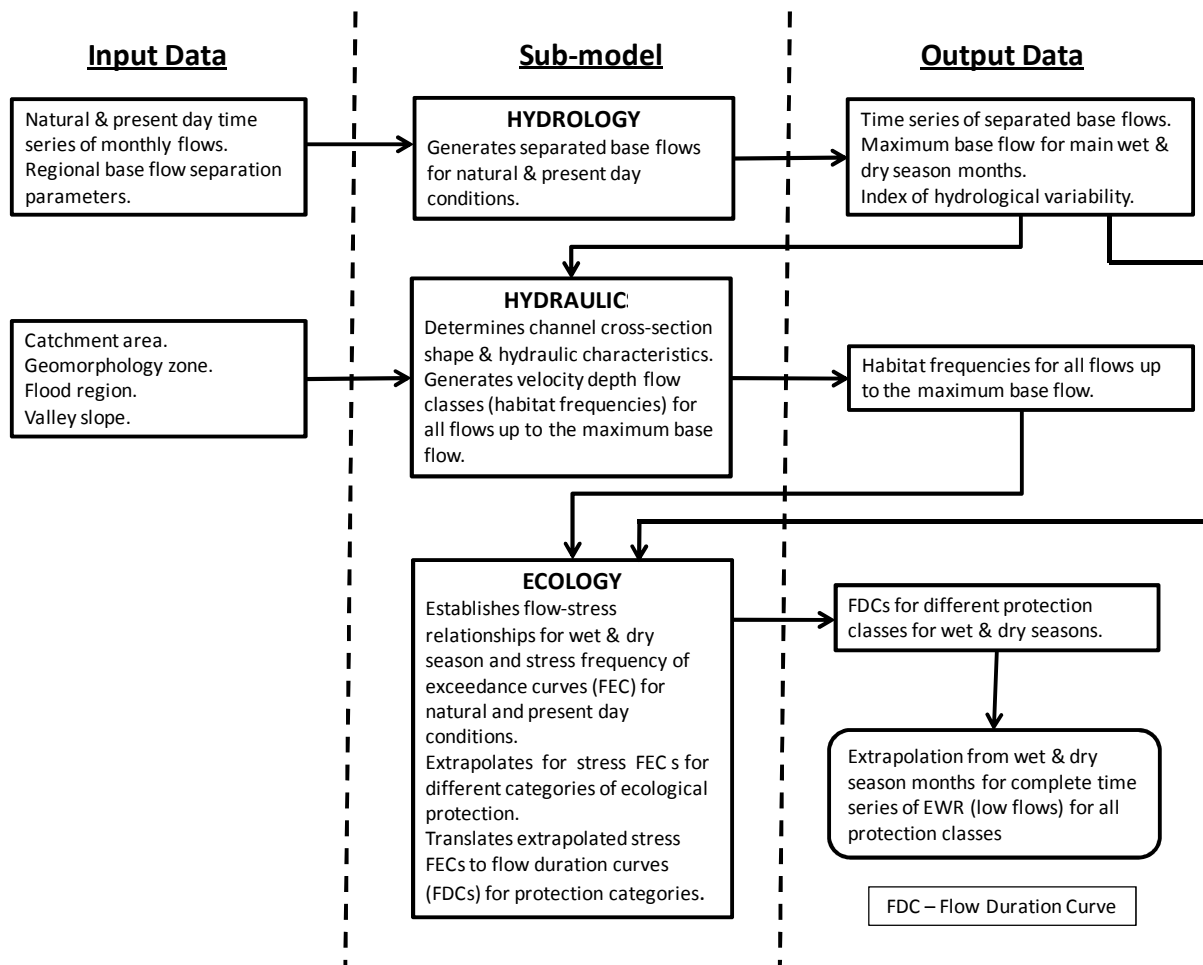
The DRM is based upon the holistic Building Block Methodology (BBM - which is discussed in Chapter 2, Section 2.1.4). The DRM utilises hydrology-flow-ecology relationships to construct a flow regime for maintaining rivers in a predetermined ecological condition. The developers of the DRM recognised that there was no widespread database on the ecological functioning of South African rivers (as required by BBM), nor would it be possible to define flow-habitat relationships for individual sites along a river within a method designed to generate very quick estimates. However, there was an extensive digital database on the natural streamflow characteristics of SA i.e. the Surface Water Resources of South Africa 1990 (WR90 – Midgely *et al.*, 1994). Hughes and Münster (2000) therefore utilised results from past EWR studies and based the flow recommendations associated with difference ecological river conditions on hydrological characteristics and specifically on the variability of the natural flow regime. Geomorphological, hydraulic and ecological considerations were

thus implicitly incorporated into the DRM along with any inconsistencies in the results that were an inevitable consequence of the developing methods of ER determination.

The DRM has proven to be a useful tool for estimating rapid, low confidence EWRs for ERs in SA. However, the model is very dependent upon the characteristics of the reference hydrology (generally naturalised) used and some assumed regional relationships between these characteristics and EWRs. Considerable advances in (i) habitat-flow-ecology relationships, (ii) regional differences in habitat-flow-ecology relationships that are related to regional differences in the natural biotic assemblages and ecological functioning and (iii) differences in the relationships between flow, habitat and hydraulics, have emerged in the last five years or so. Researchers into EFs for rivers tend to quantify the water needs of the various biotic components in terms of parameters such as water depth, flow velocity, wetted perimeter and water surface width while hydrologists, water engineers and water resource managers, on the other hand, are more comfortable expressing the water needs in terms of volume and timing. The product of hydraulic analyses and modelling comprises relationships between discharge and, among other parameters, water depth, flow velocity, wetted perimeter and water surface width (Rowlston *et al.*, 2008). Thus hydraulic results provide the essential link between the hydrological and ecological components of EFs.

A Water Research Commission (WRC) project (Project K5/1856) entitled, "*Development of a Revised Desktop Reserve Estimation Model*" was commissioned in 2009 to review and update the DRM. The main concept of the proposal was that flow-hydraulic-habitat-ecological relationships would be incorporated into the DRM through the design of hydraulic and ecological sub-models that should define the seasonal habitat requirements of the dominant species in a region for a range of levels of protection. The ecological sub-model should be linked to the hydrological sub-model through the hydraulic sub-model. The design principle of the Revised Desktop Reserve Model (RDRM) is therefore to translate habitat requirements as defined by the ecological sub-model into discharges which can then be used by the hydrological sub-model to define flow requirements. Figure 1-2 is provided as an illustration of the RDRM design and a more detailed overview of the RDRM is provided in Chapter 3. The habitat requirements should be defined in terms of velocity-depth flow classes (discussed in Chapter 2, Section 2.4.1) which would be provided by the hydraulic

sub-model. The research presented in this thesis is a direct contribution to the development of the hydraulic sub-model for the RDRM.



**Figure 1-2 Design Principle of the Revised Desktop Reserve Model**

### 1.3 Thesis Objectives

The objective of the research reported in this thesis was to produce a hydraulic sub-model that is appropriate for inclusion in the RDRM and that will provide the essential links between the ecological sub-model and the hydrological sub-model.

The design principles of the hydraulic sub-model are:

- The model should be able to operate in a desktop environment without the support of field work and the expertise of experienced individuals.

- The model should produce a realistic representation of the hydraulic conditions through hydraulic habitat modelling procedures using hydraulic parameters and characteristics estimated from readily available information for any part of SA. The degree of certainty of the hydraulic conditions estimated will vary based upon the information used.
- The development of the model should be guided by the recent developments in the science and practice of ER determinations within a South African context.

The objectives have been addressed by the following:

- Literature reviews of EF assessment methods, EWRs, open channel hydraulics, hydraulic modelling options, hydraulic data requirements and analyses for EWRs, estimation methods of hydraulic parameters, regional relationships between hydraulic parameters and available physical information.
- Establishing an approach (a predictive model) for defining a representative channel cross-section and its hydraulic characteristics based on a set of parameters that can be quantified for all rivers using readily available information (related to geomorphology, hydrology, topography etc).
- Estimation of the model hydraulic parameters using hydraulic field data obtained from past EWR studies.
- Development of estimation relationships using standard multiple regression type procedures (based on the field data) where possible, but constrained by the need for conceptually meaningful estimation approaches. The latter condition is necessary because of the relatively small amount of field hydraulic data that are available, the limitations of the data that are available for estimating parameters and the complexity of the interrelationships between the different parameters of the model. It was therefore recognised at the start of the project that these limitations may make it difficult to use standard regression type approaches without some modification. However, it was also recognised that any modifications should be based on sound conceptual principles (largely derived from the scientific literature).
- Testing of the hydraulic estimation equations across a range of different channel types to ensure that the predictions of hydraulic conditions and variations in habitat types are appropriate and likely to be representative of 'real' conditions.

- Sensitivity analyses of the hydraulic sub-model and its parameters in the context of the RDRM as a whole. This part of the project is designed to assess how uncertainties in the hydraulic sub-model predictions are likely to impact on the outputs of the RDRM as a whole, which will also be influenced by both the hydrology and ecology sub-models (and their uncertainties).

Computer programming and hydraulic models were used to develop several software programs to help achieve the objectives discussed.

## **1.4 Thesis Layout**

Literature reviews of published information related to EF methods, EWR requirements, open channel hydraulics and the role of hydraulics in EF determinations are provided in **Chapter 2**. Reviews of past research related to estimating hydraulic parameters at a desktop level are also included in **Chapter 2**. A brief overview of the RDRM is provided in **Chapter 3** followed by details of the design of the hydraulic sub-model, the data sources available for use in the development of the hydraulic estimation equations, and the sub-model's parameter and data requirements in **Chapter 4**. **Chapter 5** presents the software developed for use in the estimation of the parameters from past EWR hydraulic data. The development of the hydraulic estimation relationships are discussed in **Chapter 6**. Testing and refinement of the hydraulic estimation equations are discussed in **Chapter 7**. Analyses of the hydraulic sub-model outputs are presented in **Chapter 8**. **Chapter 9** presents the conclusions and recommendations of the thesis.

**Terminology** - It is intended that the contents of this thesis should be accessible to any organisations or individuals involved, or interested, in Environmental Flow studies. This may include hydraulic, hydrology or ecology specialists around the world. The terminology used in this thesis is largely based on that which is used by the broad community of environmental flow specialists in South Africa and there may be differences in other countries, or in other related disciplines. To ensure that there is no confusion, definitions of the terminology and abbreviations used are provided in the 'Glossary of Terms' that precedes the main text of this thesis.

## 2 LITERATURE REVIEW

Literature reviews of several topics were necessary in order to facilitate the design and development of the hydraulic sub-model. A summary of the topics reviewed is provided below and the detailed discussions of each topic are presented in the remainder of this chapter.

- **Environmental Flow Assessment Methods** – a brief discussion of the EF assessment methods developed for defining EF requirements is provided. The role of hydraulics within the methods is also discussed.
- **Open Channel Hydraulics** – an introduction to open channel hydraulics and a discussion of the commonly used flow resistance coefficients is provided.
- **Ecohydraulics** – the role of hydraulics in South African assessments is described followed by a discussion of a locally developed ecohydraulic model.
- **Describing Hydraulic Habitat** – the alternative methods of describing habitat in terms of hydraulic variables is discussed.
- **Ecohydraulic Field Data Requirements and Outputs** – hydraulic field data and hydraulic results (outputs) that are required for EWRs were investigated to identify the parameters that would be needed in the hydraulic sub-model to generate representative hydraulic characteristics and hydraulic outputs.
- **Estimation of Hydraulic Parameters** – a review of previously developed hydraulic parameter estimation equations is provided.

### 2.1 Environmental Flow Assessment Methods

Different organisms within a river ecosystem have different requirements, indicating that a diversity of conditions habitats is required to promote the biotic diversity. This observation suggests that an understanding of the full range of biotic responses to a wide range of flow impacts is required. Environmental Flow Assessment (EFA) methods were established to identify the extent to which the natural flow regime may be altered from the natural condition whilst still maintaining the integrity and functioning of the riverine ecosystem at some acceptable level (Jordanova *et al.*, 2002). An EFA produces one or more descriptions of

possible modified hydrological regimes for the river, i.e. the EFs, each linked to a predetermined objective in terms of the ecosystems' future condition (Tharme, 2003).

Detailed reviews of EFA methods are provided by Tharme (2003; 2008) and Acreman and Dunbar (2004). Tharme (2003; 2008) categorises the methods into four reasonably distinct groups and refers to them as hydrological, hydraulic rating, habitat simulation and holistic methods, although differences in the approaches to group classification do occur amongst authors (Loar *et al.*, 1986; Swales and Harris, 1995; Tharme, 1996; Jowett, 1997; Dunbar *et al.*, 1998 and Acreman and Dunbar, 2004; Gordon *et al.*, 2004).

Environmental Flow Assessments can be described as being either 'bottom-up' methods i.e. designed to 'construct' a modified flow regime by adding flow components for specific purposes to a baseline of zero flows, or 'top-down' methods i.e. the flow regime is developed by determining the maximum acceptable departure from natural conditions (Arthington *et al.*, 1998). Arthington *et al.* (1998) observe that the bottom-up holistic EFAs are likely to continue to be applied most commonly in the near future, but suggest that ultimately, the most rigorous approach would be a combined bottom-up and top-down approach. Brief reviews of the common EFA methods used in SA and internationally, according to the classification by Tharme (2003), are provided below with further details available in the referenced literature.

### **2.1.1 Hydrological Methods**

Hydrological EFA methods rely primarily on the use of natural, measured or simulated hydrological data, to advise on suitable environmental flows which may or may not be ecologically relevant (King *et al.*, 2003). These methods are low confidence, rapid and non-resource intensive. They are often referred to as fixed-percentage or look-up table methods, where a set proportion of flow represents the EF requirement (Tharme, 2003). From an ecological perspective, this type of methodology is especially simplistic in that it does not adequately address the dynamic variable nature of hydrological regimes (Tharme, 2008) and therefore of habitat availability. Hydrological EFA models include:

- **The Tenant (or Montana) Method (Tennant, 1976)**

The Tennant method has been historically the most commonly applied hydrological method in most parts of the world and comprises the specification of a fixed percentage of average flow (e.g. 20% of the daily average natural flow). Several variations of the Tennant Method have been developed using various hydrological, geomorphological, ecological or catchment based criteria to specify the minimum flow requirements under different conditions (Ptolemy and Lewis, 2002).

- **Flow Duration Curve Analysis**

Flow Duration Curves (FDCs) display the relationship between discharge and the percentage time that it is equalled or exceeded. FDCs are used to determine specific flow percentiles (percentage exceedance values) associated with required suitable river conditions to produce EF requirements e.g. the  $Q_{95}$  Method is based upon the 95% exceedance value on a seasonal FDC (Gustard *et al.*, 1987, cited in Dunbar *et al.* 1998). Smakhtin and Toulouse (1998) illustrated a strong correlation between  $Q_{75}$  and characteristics extracted from 1-day annual FDCs for different types of low-flow indices of South African rivers.

- **Range of Variability Approach (RVA, Richter *et al.*, 1997) using Indicators of Hydrological Alteration (IHA, Richter *et al.*, 1996)**

The RVA method aims to provide a comprehensive statistical characterisation of ecologically relevant characteristics of a flow regime through the setting of benchmark flows for rivers (Tharme, 2008) where protection of the natural ecosystem is the primary objective (Acreman and Dunbar, 2004). The natural range of the hydrological variation is described using hydrological indices (e.g. magnitude, timing, frequency, duration and rate of change of discharge), termed Indicators of Hydrological Alteration (IHA). The IHA method has been frequently applied to present day flow regimes to assess the degree of existing alteration and to recommend modifications to management practices to restore some degree of ecological protection.

The following two methods are categorised as hydrological EFA methods due to their strong link to hydrology but their developments implicitly include ecological data and therefore

provide additional details and confidence to the EF requirements than the other hydrological EFA methods discussed.

- **Desktop Reserve Model (DRM, Hughes and Münster, 2000; Hughes & Hannart, 2003)**

The DRM was originally designed for rapid, low confidence ER determinations (quantity component) in South Africa and was based on extrapolations from previous, higher confidence, determinations. Although based primarily on hydrology, the DRM implicitly incorporates some hydro-ecological relationships through regional parameters based on results from the application of the holistic BBM approach (Section 2.1.4).

It is based on an assumed relationship between the annual water requirements for different levels of ecological protections during both normal (referred to as maintenance) years and drought years and an index of hydrological variability. Variability within the time series of EWR is introduced using regionalised seasonal distributions and FDC shapes to specify the frequency relationships between conditions of drought to normal and greater than normal. The hydrological variability is determined by dividing the Coefficient of Variation (CV) of flows by the proportion of total flow that is considered to occur as Base Flow Index (BFI). The CV is mainly a reflection of climatic variability (cycles of wet and dry periods) and the BFI is more closely associated with the runoff generation processes that dominate in the river catchment. Rivers with variable and unreliable flow regimes would result in higher hydrological variability values which in turn result in lower low flow requirements, but greater high flow requirements than rivers with lower degrees of natural variability.

The first stage in the DRM 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 and is based on the hydrological variability values. 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 estimates into complete tables (or curves) of assurance rules (equivalent to FDCs). 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 FDC characteristics of the reference (generally naturalised) flows. This approach

is designed to ensure that sequences of high or low flow requirements reflect the same patterns of wet and dry periods as expected under natural conditions.

- **Ecological Limits of Hydrological Alteration (ELOHA, Poff *et al.*, 2009)**

The ELOHA method is a framework for assessing EF needs for many streams and rivers simultaneously, across large regions when time and resources for evaluating individual rivers is limited. The aim of ELOHA is to foster development and implementation of environmental flow standards at the regional scale.

The framework includes the synthesis of existing hydrological and ecological databases for a specific region to develop relationships between flow alteration and ecological response. This is achieved, firstly, through the development of hydrological baseline conditions for river segments throughout the region under investigation. Secondly, each river segment is classified, using a set of ecologically relevant flow variables, into a few distinctive flow regime types (also known as river types) that are expected to have different ecological characteristics. These river types can be further sub-classified according to important geomorphic features that define hydraulic habitat features. The third step is to determine the deviation of current flow conditions from baseline flow conditions. Fourthly, flow alteration–ecological response relationships are developed for each river type, for several hydrological scenarios (i.e. altered flow regimes) and is based on a combination of existing literature, expert knowledge and field studies.

### **2.1.2 Hydraulic Rating Methods**

Hydraulic Rating EFA methods are based upon the relationship between discharge and physical habitat by using hydraulic parameters such as flow depth or wetted perimeter as surrogates for determinants of habitat. The methods examine the effects of specific increments in discharge on stream habitat (Tharme, 1996) at a single cross-section. As noted by Tharme (2008), placement of the single cross-section and the quality of the relationships between discharge and hydraulic parameters are critical to the results obtained. Furthermore, explicit links with the hydrological regime are often not considered in the assessment, and the output is seldom dynamic in spatial or temporal resolutions. Hydraulic Rating EFA models include:

- **The Wetted Perimeter Method (Loar *et al.*, 1986)**

The Wetted Perimeter Method uses empirical or modelled relationships between wetted perimeter and discharge to determine minimum or preservation flows (Tharme, 2003).

- **Lotic Invertebrate Index for Flow Evaluation (LIFE, Extence *et al.*, 1999; Dunbar *et al.*, 2004)**

The LIFE method was developed in the UK utilising an extensive database from two decades of ecological surveys. LIFE assesses the biotic response to flow based on species-level and family-level preferences for flow velocity conditions, recognising that some families include taxa with variable flow requirements (Petts, 2009). An index of perceived sensitivity to water velocity was developed by allocating all recorded taxa to one of six flow groups as indicated in Table 2-1 (Orwin and Glazaczow, 2009). Procedures for using this information in the management of river flows are still under development but the principle is believed to be sound and LIFE has the major advantage of utilising the data collected by existing bio-monitoring programmes (Acreman and Dunbar, 2004).

**Table 2-1 Macroinvertebrate Flow Groups (after Extence *et al.*, 1999)**

Taxa Flow Group	Velocity Requirement
I	Rapid flows > 100 cm s <sup>-1</sup>
II	Moderate to fast flows 20-100 cm s <sup>-1</sup>
III	Slow or sluggish flows < 20 cm s <sup>-1</sup>
IV	Flowing (usually slow) and standing waters
V	Standing waters
VI	Drying out or drought impacted sites

- **Adapted Ecological Hydraulic Radius Approach (AEHRA, Liu *et al.*, 2011)**

The Adapted Ecological Hydraulic Radius Approach is a recently developed method that uses hydraulic radius as the surrogate for hydraulic habitat. The hydraulic radius is determined using the Manning flow resistance equation (Equation 2-2), surveyed or generalised cross-section and the largest 'minimum ecological velocity'. The minimum ecological velocity refers to the minimum velocity required to maintain the river course and the elementary functions of instream ecosystem components.

Although these methods take the biota into consideration, the scale and extent of the hydraulic interpretation is very limited (Jordanova *et al.*, 2004) as they fail to indicate the significance of changes in the measured physical conditions for the aquatic biota (King *et al.*, 2003). Tharme (1996) and Dunbar *et al.* (1998) consider these methodologies to be the precursors of the more sophisticated habitat simulation methods.

### **2.1.3 Habitat Simulation Methods**

Habitat Simulation EFA Methods attempt to assess flows on the basis of biotic responses at the level of instream habitat (Tharme, 2008). They combine physical habitat and habitat preferences of a target species to estimate the amount of habitat available over a range of discharges (Jordanova *et al.*, 2004). The methods use one or more hydraulic variables, with the most common being flow depth, velocity, substratum composition and benthic shear stress (Tharme, 1996). Habitat simulation methods provide a means of assessing environmental flows in situations where competition between instream and offstream uses are likely to be controversial (Estes, 1996), or where the river system and/or some of its components are of exceptional conservation importance (Tharme, 1996). Habitat Simulation EFA models include:

- **Instream Flow Incremental Methodology (IFIM, Reiser *et al.*, 1989)**

Instream Flow Incremental Methodology (IFIM) essentially comprises a set of analytical procedures and computer models. Using a combination of hydraulic, hydrological and biological data, IFIM evaluates the effects of incremental changes in streamflow on channel structure, water quality, temperature and availability of suitable habitat (Pusey, 1998). IFIM has been developed in conjunction with the Physical Habitat Simulation Model (PHABSIM, Bovee, 1986; Milhous *et al.*, 1989; Nestler *et al.*, 1989; Stalnaker *et al.*, 1994). PHABSIM is a hydraulic model that simulates hydraulic conditions over a range of discharges with the simulations then linked to habitat information for the target species (King and Tharme, 1994). PHABSIM comprises hydraulic and physical habitat simulation procedures. The results of the simulation procedures are linked to produce an output of Weighted Usable Area (WUA, Section 2.4.2) versus discharge. The WUA relationships quantify changes in habitat, described by some combination of depth, velocity substratum and cover, for the target species, lifestyles or species assemblages of concern. Breakpoints on the WUA-discharge

curves, interpreted as thresholds below which habitat quality becomes significantly degraded, are used to recommend EFs (Tharme 2003, 2008).

The IFIM has been the most commonly used environmental method worldwide (Tharme 2003) and it was applied in SA on the Olifants River, Western Cape (Gore *et al.*, 1991; King and Tharme, 1994). King and Tharme (1994) concluded that IFIM was not applicable to South African river conditions for four main reasons:

- i. It is difficult and time-consuming to learn as it incorporates concepts and skill from a wide range of disciplines.
- ii. It is difficult to apply as it was vague, non-pragmatic or still largely conceptual.
- iii. PHABSIM is complex and difficult to master.
- iv. It did not allow compilation of a comprehensive modified flow regime for a regulated river in the way required in SA.

Tharme (2008) further noted that IFIM only represents one of a suite of tools required for a complete EFA and cannot be readily used for certain components of the riverine ecosystem e.g. riparian vegetation and issues pertaining to long-term geomorphological changes. Such methodologies remain biased towards the assessment of the EF requirements of target fish species. This bias was based on the understanding that these target species are very sensitive and thus if the EF is appropriate for them, it will be appropriate for other components of the ecosystem (Acreman and Dunbar, 2004). Recent efforts have concentrated on major advances in multidimensional habitat modelling and the inclusion of complex, spatially explicit habitat metrics (Tharme, 2003).

- **Other Habitat Simulation Methods**

Dunbar *et al.* (1998) and Tharme (1996; 1997; 2000) cite several other habitat simulation models and methods of similar character and with many of the same data requirements as the PHABSIM component of IFIM. The most apparent trend common to these models is a move towards increasingly advanced hydraulic and habitat modelling (Tharme, 2003). The following examples were cited by Tharme (2003); the use of two- and three- dimensional levels of resolution (Ghanem *et al.*, 1996; Hardy, 1996; Blažková *et al.*, 1998; Crowder and Diplas, 2000), the inclusion of complex, spatially explicit habitat metrics, and the use of

geographical information system-based spatial display platforms (Waddle, 1998). A list of habitat simulation methods and their references or cited references discussing or reviewing the methods is provided in Table 2-2.

**Table 2-2 Other Habitat Simulation Methods (compiled using information from Tharme, 2008)**

Habitat Simulation Method	Description	Reference
River Hydraulics and Habitat Simulation Program (RHYHABSIM)	A simplified version of PHABSIM developed in New Zealand	Jowett and Richardson (1995); Jowett (1989)
Riverine Habitat Simulation Program (RHABSIM)	A commercial version of PHABSIM developed in the USA	Dunbar <i>et al.</i> (1998); Payne & Associates website (2011)
Computer Aided Simulation Model for Instream Flow Requirements (CASiMiR)	A simulation model developed for assessment of EFs in rivers regulated by hydropower schemes	Statzner and Higler (1986); Statzner <i>et al.</i> (1988); Jorde (1996)
River System Simulator (RSS)	A simulation model developed in Norway for application to rivers regulated by hydropower schemes.	Alfredson (1998)
Riverine Community Habitat Assessment and Restoration Concept (RCHARC)	A variant of IFIM developed to identify a flow regime that results in similar spatial distribution of depth and velocity conditions to that occurring before impoundment	Nestler <i>et al.</i> (1994), cited in Richter <i>et al.</i> (1997)
Evaluation of Habitat Method (EVHA)	A variant of PHABSIM developed in France	Ginot (1995), cited in Dunbar <i>et al.</i> (1998)
HABIOSIM	A microhabitat modelling system developed in Canada	Dunbar <i>et al.</i> (1998)

#### 2.1.4 Holistic Methods

Holistic methods quantify the EF requirements for the various biotic components of rivers in terms of hydraulic parameters such as flow depth, flow velocity and wetted perimeter, and adding temporal variability by referring to the frequency of exceedance of a particular flow rate, or the duration of inundation resulting from a particular flooding event (Tharme, 1996). In the holistic approach, important and/or critical flow events are identified in terms

of select criteria defining flow variability i.e. magnitude and timing, and are based on explicit links between changes in flow regime and the consequences for the biophysical environment (Tharme, 2003).

King *et al.* (2003) note that holistic all methods are based on the same philosophy, i.e. to manage the condition of a river,

- i. all major abiotic and biotic components constitute the ecosystem to be managed, and
- ii. the full spectrum of flows, including their temporal and spatial variability, constitutes the flows to be managed.

The holistic methods essentially comprise processes which allow practitioners from several disciplines to integrate data and knowledge. Each specialist uses the methods of their choice to develop an understanding of flow-ecosystem relationships. Thereafter, the specialists work collectively, within the overarching process of the holistic approach, to reach consensus on the EF required (King *et al.*, 2003).

The most advanced holistic methods routinely utilise several of the tools for hydrological, hydraulic and habitat analysis featured in the three types of EFAs (hydrological, hydraulic rating and habitat simulation), within a modular, structured framework for establishing environmental flows (Tharme, 2008). Tharme (2003) lists approximately 16 holistic methods, applied in Australia, SA and the UK, that have contributed greatly to the field of EFAs. A list of the common holistic methods and their references or cited references discussing or reviewing the methods is provided in Table 2-3.

A recently developed South African approach, the Flow Stressor-Response (FS-R) approach (O’Keeffe *et al.*, 2002; O’Keeffe and Hughes, 2004; Hughes and Louw, 2010) along with other Southern African approaches (BBM and Downstream Response to Imposed Flow Transformation, DRIFT) are discussed below.

- **Building Block Methodology (BBM, King and Tharme, 1994; King, 1996; Tharme and King, 1998; King and Louw, 1998; King *et al.*, 2008)**

The conceptual basis of the BBM is that some flows within the total flow regime are more important than others for maintenance of the river ecosystem, and that these flows can be identified and described in terms of their magnitude, duration, timing and frequency (King & Louw 1998; Tharme & King, 1998; King *et al.*, 2008). These flows are the ‘building blocks’ of a modified flow regime for both maintenance and drought conditions, and in combination with high flows, constitute the EWR associated with a specified level of protection.

- **Downstream Response to Imposed Flow Transformation (DRIFT, King *et al.*, 2003; Brown and King, 2000)**

The DRIFT method is based on the same conceptual tenets and multidisciplinary, workshop-based interaction as the BBM and the Australian Holistic Approach (see Table 2-3 and King *et al.*, 1999; Tharme, 2003). However, it focuses on the identification of a series of river water levels associated with a particular set of biophysical functions and specific hydrologic and hydraulic character (Tharme, 2008). DRIFT is a scenario based process for addressing the ecological and socio-economic consequences of progressive reduction in flows (Brown and King, 2000). It is essentially a data-management tool, allowing data and knowledge to be used to their best advantage in a structured process. The method was developed to overcome two major weaknesses of BBM (King *et al.*, 2003), firstly, it is essentially prescriptive (i.e. a river condition is specified, and then the recommended flow regime to achieve it is described) and secondly, it does not adequately address the impacts of changing rivers on subsistence users.

- **Flow Stressor-Response (FS-R, O’Keeffe *et al.*, 2002; O’Keeffe and Hughes, 2004; Hughes and Louw, 2010)**

The FS-R method guides the evaluation of the ecological consequences of modified flow regimes using an index to score flow-related ‘stress’. The ‘stress’ response of biota to different flows is determined through an assessment of habitat conditions at these flows. The original FS-R method has been extended to the Habitat Flow Stressor-Response (HFS-R) approach, with ecologically relevant hydraulic habitat (e.g. depth, velocity, inundated

substrate and vegetation) being interpreted in terms of its usefulness to biological habitat requirements (Birkhead, 2010). The HFS-R method uses relationships between low flows and corresponding ecological 'stresses' to generate time series of stress indices, linked to a river's flow regime. These stress regimes allow for the examination of a range of flow scenarios, each with expression of the potential risk of change in the river ecological condition (Tharme, 2003).

The HFS-R method is flexible enough to deal with a wide variety of different impacts regardless of whether they are associated with critical thresholds, with frequencies of occurrence, with durations above or below defined 'stress' indices or with variations in the relevance of 'stress' levels across different seasons (Hughes and Louw, 2010). The term 'stress' in the HFS-R model should be interpreted as a flow that causes an instantaneous 'stress' and that the 'stress' indices are thresholds of hydraulic habitat conditions (and therefore flow) that will impact on ecological functioning if they persist for certain lengths of time (Hughes and Louw, 2010). The 'stress' indices range from 0 (i.e. natural conditions and hence no 'stress') to 10 (i.e. zero flow and hence extremely 'stressed'). It is important to note that the HFS-R approach is currently limited to dealing with the relatively continuous low flow component of the EWR and alternative approaches are required to specify the event-based high flow component (freshes and floods) of the EF requirement.

There is no simple choice for which method is best or most appropriate (Acreman and Dunbar (2004). However, King *et al.* (1999) and Tharme (2003) consider holistic methodologies more appropriate, particularly from the perspective of developing countries. This is due to the need of such countries to focus on protection of the resource at an ecosystem scale, as well as the strong livelihood dependencies on the goods and services provided by aquatic ecosystems. Holistic methodologies are considered most appropriate for South African conditions, where there are constraints in terms of, inter alia, historical hydrological, ecological and geomorphological data for the river system of concern; limited finances; extreme time pressures associated with the need to plan future water resources development projects; and limited manpower and expertise (Tharme, 2008). Any method that can be considered scientifically acceptable should account for the relationships between flow and ecological response, either implicitly or explicitly.

**Table 2-3 Other Holistic Methods (compiled using information from Arthington *et al.*, 2004 and Tharme, 2008)**

Holistic Method	Description	Reference
Building Block Methodology (BBM) (bottom-up approach)	Refer to a more detailed description in Section 2.1.4	King and Tharme (1994); King (1996); King and Louw (1998); Tharme and King (1998); King <i>et al.</i> (2008)
Holistic Approach (bottom-up approach)	Developed in parallel with the BBM in Australia and shares the BBM's basic tenets and assumptions. The method is a systematic construction of a modified flow regime, on a month-by-month and element-by-element basis. Each element represents a well defined feature of the flow regime intended to achieve particular ecological, geomorphological or water quality objectives in the modified river ecosystem.	Arthington <i>et al.</i> (1992); Tharme (1996); Arthington (1998). Reviews in Growns and Kotlash (1994); Tharme (1996, 2003); Arthington and Lloyd (1998); Dunbar <i>et al.</i> (1998)
Downstream Response to Imposed Flow Transformations (DRIFT) (top-down approach)	Refer to a more detailed description in Section 2.1.4	Brown and King (2000); Arthington <i>et al.</i> (2003); King <i>et al.</i> (2003)
Expert Panel Method (EPAM) (bottom-up approach)	Developed in Australia, it is the first multidisciplinary, panel-based approach. The method aims to address river ecosystem health, rather than the health of single components. It relies on ecological interpretation, by a panel of experts in aquatic ecosystems and river management, of multiple trial flow releases from an impoundment. The recommended, modified, flow regime may be determined at one or more downstream sites.	Swales <i>et al.</i> (1994); Swales and Harris (1995); Arthington (1998) Reviews in Growns and Kotlash (1994); Tharme (1996, 2000); Dunbar <i>et al.</i> (1998)
Scientific Panel Assessment Method (SPAM) (bottom-up approach)	The SPAM approach shares many of its philosophical and methodological procedures with the BBM and Holistic Approach. It is considered a more sophisticated version of EPAM in which the key features of the ecosystem and hydrological regime and their interactions at multiple sites are used as the basis for EF requirements.	Thoms <i>et al.</i> (1996); Arthington (1998)
Habitat Analysis (bottom-up approach)	Developed in Australia, its primary role is a planning tool for water-resource development at a catchment scale. The Habitat Analysis has similar tenets to the BBM and Holistic Approach and,	Walter <i>et al.</i> (1994); Burgess and Vanderbyl (1996);

Holistic Method	Description	Reference
	in its initial form, uses habitat as a surrogate for assessing the EF requirements of aquatic biota. It does not focus directly on the needs of individual target species or communities. The method has evolved to include the expert panel methodologies (i.e. EPAM and SPAM), and further evolved to more explicitly focus on the flow requirements of the whole riverine ecosystem.	Arthington (1998); Burgess and Thoms (1998)
Flow Restoration Methodology (FLOWRESM) (bottom-up approach)	Developed in Australia, FLOWRESM represents a hybrid of the Holistic Approach and BBM, where the emphasis in the identification of the essential features of the hydrological regime is on those flows that need to be built back into the regime to shift the regulated river system in the direction of the pre-regulation state.	Arthington <i>et al.</i> (1999); Arthington <i>et al.</i> (2000); Tharme (2003)
River Babingley (Wissey) Method (bottom-up approach)	Developed in the UK, specifically for the application in groundwater-dominated rivers. The method defines an “Ecologically Acceptable Flow Regime” (EAFR) which is synthesised from benchmark flows, flow frequencies and flow duration. The benchmark flows are related to the specification of ecological objectives comprising of specific targets.	Petts (1996); Dunbar <i>et al.</i> (1998); Petts <i>et al.</i> (1999)
Flow Management Plan (bottom-up approach)	Developed in SA for the specific use in highly regulated river systems that will need to be managed in such a state in the future.	Muller (1996, 1997)
Benchmarking Methodology (top-down approach)	Developed in Australia, this method is particularly suitable for the generation of risk assessment frameworks for basin-scale evaluation. Furthermore, the Benchmarking Methodology has become established as an independent method, suitable for poorly studied systems. The process requires the identification of various indicators of critical flow events, and calculation of changes in these indicators linked to degrees of ecological degradation to produce “benchmarks”. The benchmarks are then compared with the river’s pre-regulation conditions. Comparisons amongst catchments with similar levels of flow regulation or ecological characteristics can also be made.	Arthington (1998); Bunn (1998); Brizga <i>et al.</i> (2001, 2002)
Adapted BBM-DRIFT (top-down approach)	Developed in Zimbabwe in response to the requirements in the new water legislations for EFAs	Steward <i>et al.</i> (2002)
Flow- Stressor Response Method (FS-R) (top-down approach)	Refer to a more detailed description in Section 2.1.4	O’Keeffe <i>et al.</i> (2002); O’Keeffe and Hughes (2004a); Hughes and Louw (2010)

The application of habitat simulation and holistic methods to set EF requires an interface between hydrology and ecological factors. Researchers in EFs for rivers tend to quantify the water needs of the various biotic components in terms of hydraulic parameters such as water depth, flow velocity, wetted perimeter and surface width, whereas hydrologists, water engineers and water resource managers are more comfortable expressing the water needs in terms of volume and timing (Rowlston *et al.*, 2008). This essential interface is found in the hydraulic analysis of flow in natural open channels.

The hydraulic requirements for EFAs are dependent upon various factors such as the type of issue that needs to be addressed, specification of the actual hydraulic variables to be used (e.g. depth, velocity, turbulence characteristics), the dimensions and resolution at which they should be described (e.g. velocity as a cross-sectional average, a distributed depth average or a full three-dimensional description) and what spatial (e.g. shape, location, gradient) and temporal (e.g. duration, timing, rate of change, frequency) characteristics are necessary.

Fundamentally, the hydraulic requirements for the South African developed DRIFT and HFS-R holistic methods are identical. They involve the characterisation of the discharge-related, ecologically relevant hydraulic habitat for sites along river systems. Traditional methods of hydraulic data and analysis have evolved over the past two decades to meet this need, in parallel with the development and refinement of the EFA methods (Birkhead, 2010). A brief discussion of open channel flow is provided below followed by a discussion of the role of hydraulics in EFAs.

### **2.1.5 General Discussion of Environmental Flow Assessment Methods**

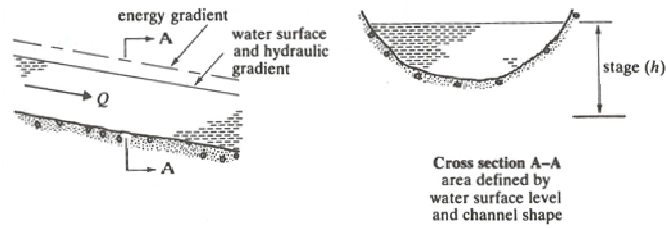
A degree of subjectivity, from the specialists used, is inherent in many of the detailed EFA methods. The trend has been to reduce the subjectivity by improving the understanding of the underlying science and therefore increase the reliability and repeatability of the results. One of the problems is the lack of hard information and data on the complex relationships between hydrology, hydraulics and ecology. Concepts may be reasonably clear but site specific information is often not. Approaches are to utilise specialist knowledge to overcome the lack of hard data, but this is often not possible for practical purposes. Desktop

approaches are valuable for management and, from a scientific point of view they need to be aligned with the concepts and understanding that are applied in more detailed studies. Generally, the principle of holistic methods has become the preferred method of choice when undertaking EF studies and incorporating these principles into the desktop approaches is necessary.

## **2.2 Open Channel Hydraulics**

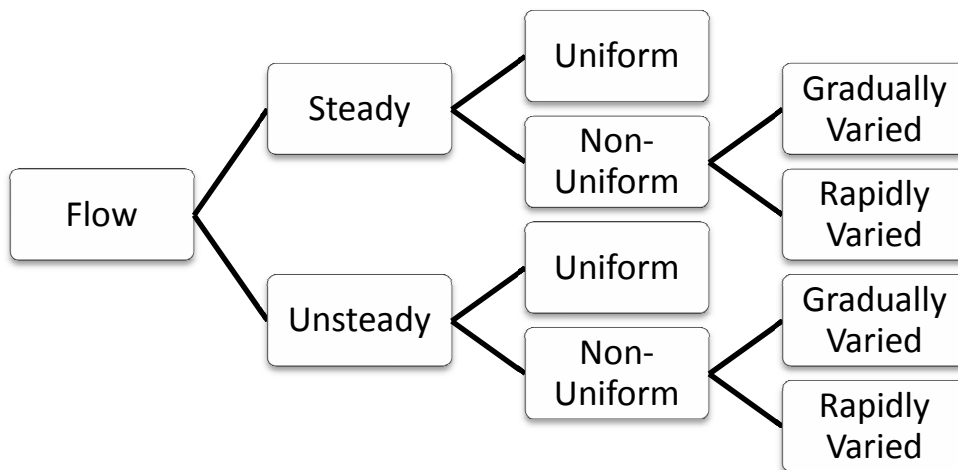
Rivers are highly complex and dynamic systems that are continuously evolving. They adjust in response to human activities and changing climatic, geologic and hydrologic regimes. The adjustments can be observed through changes in resistance to flow, velocity, gradient, depth, width and planform. In order to effectively determine the flow characteristics in a river, open channel hydraulic analyses are undertaken. Principles of fluid mechanics have been established for many years and the mechanics of uniform flow were first treated mathematically by Chézy (1775). Three fundamental physics laws; conservation of matter (or mass), energy and momentum, are assumed by scientists during the development of relationships to describe the flow of a fluid (specifically water in the case of river flow) and further details of these conservation laws and other open channel basic concepts may be found in the standard textbooks of Chow (1959), Henderson (1966), French (1985) and/or Chaudhry (2008).

Open channel flow is characterised by the existence of a free surface (the water surface). The longitudinal profile of the free surface defines the hydraulic gradient and the cross-sectional area of flow is defined by the water surface level or stage and channel shape (Figure 2-1). The stage illustrated in Figure 2-1 defines the position of the free surface at any point in the channel. Flow depth is the vertical distance of the lowest point of a channel section from the free surface. Thus the stage is equal to the flow depth if the datum is selected as the lowest point of the channel section (Chadwick and Morfett, 1998).



**Figure 2-1 Channel Flow (after Chadwick and Morfett, 1998)**

Flow may be classified into several types based upon time and space (Figure 2-2). Steady flow occurs when the parameters of flow are constant with respect to time and unsteady flow occurs when the parameters of flow changes with time. Uniform flow occurs when the parameters of flow are constant at every point along the flow path and non-uniform flow occurs when the parameters of flow vary from point to point along the flow path. Non-uniform flow is further classified gradually varied flow (GVF) or rapidly varied flow (RVF) - Figure 2-3. GVF occurs when the change in flow depth with respect to distance is small and RVF occurs when the change in flow depth with respect to distance is large. In GVF, frictional effects cannot be ignored. RVF is observed when there is a sudden change in the geometry of the channel or flow regime.

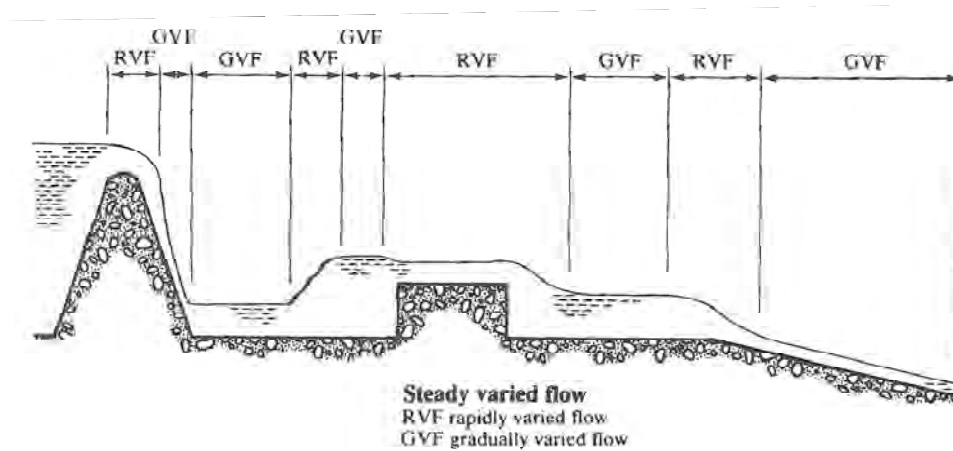


**Figure 2-2 Classification of Flows**

Richards (1982) noted that various theoretical open channel flow models involve simplifying assumptions concerning the spatial (uniform, non-uniform) and temporal (steady, unsteady) variations of flow properties. Generally, the flow in a river is unsteady and non-uniform due to the time-varying discharge and irregular channel geometry i.e. expansions and

contractions in cross-section shape or changes in slope or roughness (Chow, 1959). The underlying assumption in GVF computations is that the headloss over a reach is equal to the headloss in the reach for a uniform flow having the same hydraulic radius and average velocity (French, 1985). This assumption allows uniform flow relationships to be used to model the energy slope of a GVF at a specific cross-section. It also allows the roughness coefficients (refer to Section 2.2.1), developed for uniform flow, to be applied to varied flows (US Army Corps of Engineers, 1993). The US Army Corps of Engineers (1986) state that the uniform flow assumption was never confirmed by experiment or theory but that the errors resulting from them are known to be small in comparison to other errors such as roughness estimation and surveyor error.

In EF studies, a river length is delineated into reaches primarily based upon ecological diversity, and hydraulic analyses are then carried out on these reaches. The site selected within a reach represents GVF conditions and uniform flow is assumed during the ecohydraulic analyses (refer to Sections 2.3 and 2.4 for further details regarding ecohydraulic analyses and site selection).



**Figure 2-3** Types of Flow that may Occur in Open Channels (after Chadwick and Morfett, 1998)

### 2.2.1 Open Channel Flow Resistance

The behaviour of open channel flow is governed by the effects of flow resistance and gravity relative to the inertial forces of the flow. Uniform flow conditions require that gravity forces must exactly balance the frictional resistance forces which constitute the boundary shear force (Equation 2-1).

$$\tau_o = \gamma R S_f \quad 2-1$$

where	$\tau_o$	Boundary shear stress ( $\text{N m}^{-2}$ ),
	$R$	Hydraulic radius (m), equal to the ratio of the cross sectional area ( $A$ , $\text{m}^2$ ) to the wetted perimeter ( $P$ , m),
	$S_f$	Energy gradient, the gradient may be represented by the bed gradient ( $S_o$ ) for uniform flow, and
	$\gamma$	Specific weight of the fluid ( $\text{kg m}^{-2} \text{s}^{-2}$ ), equal to the product of density ( $\rho$ , $\text{kg.m}^{-3}$ ) and gravitational acceleration ( $g$ , $\text{m s}^{-2}$ )

The conventional approach to describe frictional resistance is based on the assumed proportionality between boundary shear and the square of the average velocity, with the resistance accounted for by a single coefficient of resistance (Bathurst, 1982). The most commonly used relationships for frictional resistance are:

- Manning  $n$  
$$n = \frac{1}{V} R^{2/3} S^{1/2} \quad 2-2$$

- Darcy-Weisbach  $f$  
$$f = \frac{8g}{V^2} R S \quad 2-3$$

- Chézy  $C$  
$$C = \frac{V}{\sqrt{R S}} \quad 2-4$$

where	$V$	Cross-sectional average velocity ( $\text{m s}^{-1}$ ),
	$R$	Hydraulic radius (m),
	$S$	Energy or bed gradient,
	$g$	Gravitational acceleration ( $\text{m s}^{-2}$ ),
	$n$	Manning resistance coefficient ( $\text{s m}^{-1/3}$ ),
	$f$	Darcy-Weisbach resistance coefficient ( $\text{s m}^{-1/3}$ ), and
	$C$	Chézy resistance coefficient ( $\text{m}^{1/2} \text{s}^{-1}$ )

Manning's and Chézy coefficients were empirically derived from data collected on artificial and natural channels with a range of shapes and bed materials. The Darcy-Weisbach coefficient was theoretically derived. The American Society of Civil Engineers Task Force on Friction Factors in Open Channels (1963) recommended the use of the Darcy-Weisbach equation, noting that it was based on more fundamental research. However, Yen (2002) stated that the Darcy-Weisbach  $f$  is more appropriately used for point resistance while Manning's  $n$  is used for cross-sectional and reach resistance. Furthermore flow resistance is typically quantified by Manning's  $n$  in practical river hydraulic applications because of its simplicity and there is generally more data available compared to the other two resistance coefficients. Table 2-4 lists several documented sources of Manning's  $n$  coefficients. However, the resistance relationships may be interchanged conveniently as the coefficients are related as follows:

$$\frac{1}{\sqrt{g}} \frac{R^{1/6}}{n} = \frac{c}{\sqrt{g}} = \sqrt{\frac{8}{f}} \quad 2-5$$

Flow resistance estimation is the largest source of uncertainty in river hydraulic modelling (Birkhead, 2010) but is an essential input to deterministic hydraulic modelling at all levels of resolution and a crucial step for linking the occurrences of water in rivers with their ecological functioning (James, 2010).

The theories of open channel resistance are presented in publications such as Leopold *et al.* (1960), Rouse (1965), Bathurst (1982) and Yen (2002). Rouse (1965) proposed the classification of flow resistance into four categories and referred to them as (i) surface resistance, (ii) form resistance, (iii) wave resistance and (iv) resistance associated with flow unsteadiness or local acceleration.

All four resistance types occur in natural river systems. The main types of resistance accounted for in ecohydraulic modelling (Section 2.3) are surface and form resistances. Surface resistance results from the shear stress at the boundary in contact with the flow, producing shear and associated viscous and turbulent energy dissipation through the flow. Surface resistance is always present, but may be dominated by other types in some situations. Form resistance results from the asymmetrical distribution of pressure and the

dissipation of turbulent energy produced by flow separation around submerged or partially submerged boundary irregularities. This type also includes resistance associated with flow patterns induced by the channel form, such as secondary circulation around bends. Form resistance is associated with channel irregularities ranging in scale from micro-roughness features such as pebble clusters, through alluvial bed forms to channel bars and pool-riffle sequences, as well as vegetation. Details of developments in flow resistance to account for the distinct contributions of each resistance type on open channel flow have been recently reviewed by James (2010) and are not repeated here.

The Manning, Darcy-Weisbach and Chezy resistance equations were specifically developed, and are appropriate, for describing surface resistances only and are thus inappropriate for low flow, form resistance conditions. However, most results presented to date do not explicitly account for the different resistance phenomena with the resistance coefficients being a lumped parameter accounting for all the various influences in a river reach. A single resistance coefficient that accounts for different features and types of roughness is used in the modelling (i.e. a composite roughness coefficient) and is determined by one of the methods tabulated in Table 2-4.

### **2.3 Ecohydraulics**

Hydrological data on river flow quantify the volume of water that moves through any chosen point along the river system over a chosen time period (i.e. flow rate). Such data are applied at the catchment level and are appropriate for assessing the ecological response to temporal flow variations. However, the data are unable to provide details of the forces acting on the river system or on the conditions directly experienced by the biota. Biotic responses to variations in flow rate can be assessed through the variations in local hydraulic conditions such as depth, velocity and inundated area. Transforming flow rate data into measures of depth, velocity and other hydraulic variables is dealt with by the discipline of hydraulics (Paxton and King, 2010), specifically ecohydraulics in EF studies.

**Table 2-4 Documented Sources of Manning's  $n$**

	<b>Source of Manning's <math>n</math> Coefficient</b>	<b>Description</b>	<b>Comments</b>
<b>Tables of Manning <math>n</math></b>	Chow (1959), French (1985)	Tables of typical Manning $n$ values for various materials and channel conditions are provided.	These publications provide a good initial source of roughness values. They are largely superseded by the photographic matching guides.
<b>Photographic Matching Guides</b>	Barnes (1967), Arcement and Schneider (1989), Annable (1996)* Hicks and Mason (1998), Marsh <i>et al.</i> (2001) Ladson <i>et al.</i> (2003), Wohl and Wilcox (2005)*, Desai (2007)	Photographic matching guides have been developed containing calibrated roughness coefficients linked to photographs of the river conditions at the time of field data collection.  Roughness coefficients are then estimated for unstudied sites by matching similarities between it and the calibrated sites. Similarities in geometry, sediment, vegetation, hydrology and hydraulic characteristics are matched.	These guides may be used to (i) obtain a resistance coefficient for use in hydraulic modelling, (ii) as verification for other roughness estimation methods or (iii) as an initial estimate for use in other roughness estimation methods.
<b>Synthesis of Composite Manning Coefficients</b>	Cowan (1956) and further developed by the United States Soil Conservation Services Method (SCS) (1963), Arcement and Schneider (1989), HR Wallingford (2004)	A method for synthesising the overall resistance of a channel. It involves the selection of a basic value of Manning's $n$ for a uniform, straight and regular natural channel. The basic value is then adjusted for the effects of surface irregularities, shape and size of channel cross section, obstructions, vegetation and flow conditions and the meandering of the channel.	The adjustments may be the linear (SCS, 1963; Arcement and Schneider, 1989) or squared (HR Wallingford, 2004). The linear superposition of effects has been found to be not credible but the summation of squares of values does have theoretical justification (James, 2010).
	Pavlovski (1931); Horton (1933)	A method for synthesising the overall resistance of a channel. It involves the sub-division of the cross-section into sub-sections, each having a local resistance value. A composite roughness for the cross-section is obtained through the combination of the sub-sections.	The influences between sub-sections are ignored and velocity in all sub-sections is assumed to be the same.

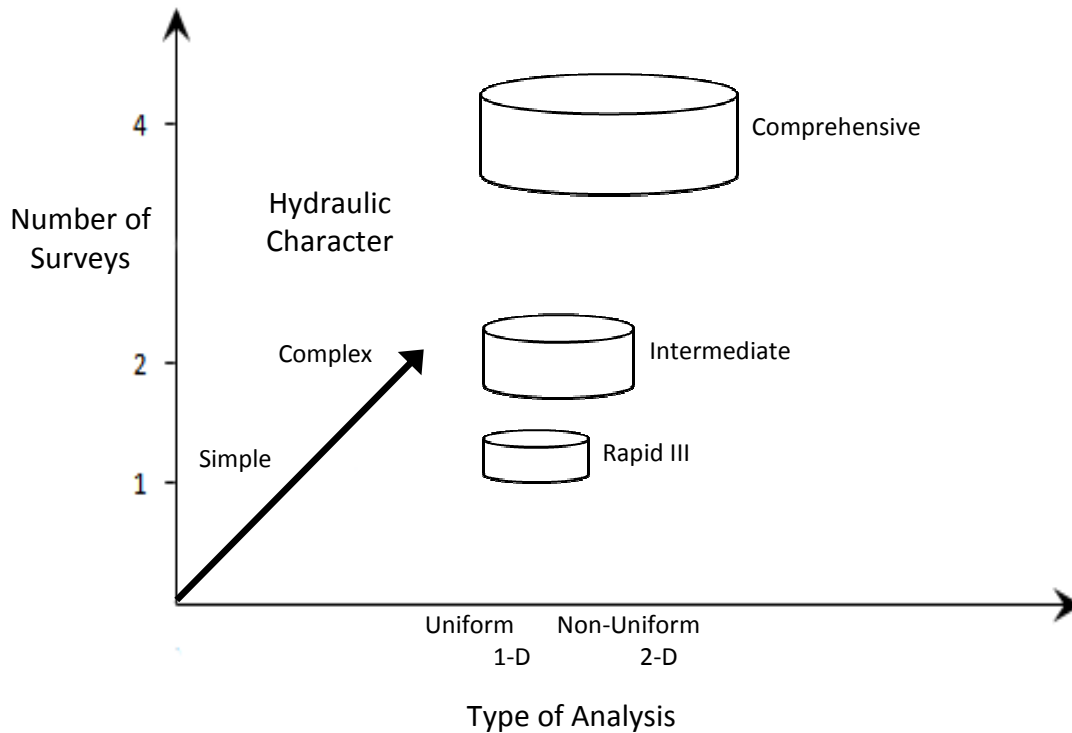
\* Not a photographic matching publication but contains additional information compared to the simple Manning table publications

Ecohydraulics is defined as the study of the linkages between physical processes and aquatic ecosystems (Centre for Ecohydraulic Research, 2011). Ecohydraulic modelling is employed to predict how hydraulic conditions in a river system might change under different hydrological regimes and thus, how the aquatic habitat of specific species or communities could be affected (James and King, 2010). These hydraulic conditions may be obtained by direct measurement at the site of interest, or by prediction through modelling. A combination of these two is normally used to obtain the final hydraulic conditions for the site.

Any holistic EFA method requiring site-specific assessments will need basic hydraulic information. The information is obtained through the collection of field data which is then used in different methods of analysis to provide a set of relationships between flow rate, stage or maximum flow depth, average cross sectional velocity and area of inundation.

### **2.3.1 Ecohydraulics in South Africa**

In SA, the role of ecohydraulics changes very little with the different ER levels (Rapid III, Intermediate or Comprehensive). However, different amounts of field data are collected for the different ER levels and this has implications on the hydraulic uncertainty associated with the results. Ecohydraulic applications for the ER therefore require appreciation of the interdependence between data collection, method of hydraulic analysis, site characteristics, and uncertainty. These relations are illustrated graphically in Figure 2-4, which shows the influences of data collection (specifically the number of field surveys), type of hydraulic analysis, and hydraulic character of the river site on the specification of the Reserve level (Birkhead, 2010).



**Figure 2-4 Relations between Reserve level, number of surveys, site character and type of hydraulic analysis (after Birkhead, 2010)**

The graphic in Figure 2-4 may be interpreted as follows (Birkhead, 2010):

- Rapid Reserve assessments employ simple methods of analysis (e.g. 1-D uniform, refer to Section 2.3.2 for further details) to characterise the simplest hydraulic conditions in the field (that are nonetheless useful for making ecological interpretations), to provide an accurate low-flow rating for discharges near the single measured value;
- Intermediate Reserve assessments may employ more rigorous methods of analysis (1-D non-uniform) if warranted by more complex hydraulic conditions, to provide an accurate rating (generally low-to-medium or low-to-high flow) for discharges interpolated from measured values; and finally;
- Comprehensive Reserve assessments may employ even more rigorous and complex methods of analysis (1-D or 2-D non-uniform) if warranted by even further hydraulic complexity to provide an accurate rating within the range of measured flows. Ideally, the range of recommended flows should be within the range of measured values, and for this reason field surveys are scheduled over a hydrological wet season.

### 2.3.2 Ecohydraulic Modelling in South Africa

Numerous deterministic one-dimensional (1-D) and two-dimensional (2-D) hydraulic models have been developed and are used to describe both steady and unsteady flow. Other than considering the advantages and disadvantages of the many hydraulic models available, one needs to also take into account the level of the ER determination, the output requirements, the levels of accuracy and precision required and the resources of time, money, effort and information available (Birkhead, 2010).

One-dimensional hydraulic modelling considers flow in the longitudinal direction of the river only and velocities are treated as average cross-sectional values. 2-D hydraulic modelling considers flow in the longitudinal and lateral direction of the river and thus provides an assessment of depth connectivity and predicts the distribution and point locations of depth and velocity across the modelled reach. 2-D hydraulic analyses require additional topographical and hydraulic data (for model development and calibration) as well as boundary rating functions. James (2010) emphasises that a high resolution model (e.g. 2-D) is not necessarily better than a lower resolution model (e.g. 1-D). For example, it is meaningless to describe the hydraulic conditions at a higher resolution than the available Habitat Suitability Criteria (HSC, discussed in Section 2.4.2) can use. Birkhead (2010) further advises that sites where 1-D analyses can sensibly be applied are favoured for ER determination purposes in SA, due to resource constraints. For more hydraulically complex sites, the preference is for collection of additional field data rather than more rigorous hydraulic modelling.

Hirschowitz *et al.* (2007) presented an extensive review of hydraulic models and provides the following recommendations for application in SA:

- Hydrological Engineering Centre's – River Analysis System (HEC-RAS) - developed by the Institute for Water Resources, US Army Corps of Engineers (Brunner, 2010; Brunner and CEIWR-HEC, 2010; Warner *et al.*, 2010). HEC-RAS is a 1-D hydraulic modelling software for non-uniform and unsteady flows in natural and artificial channels. HEC-RAS has been successfully applied to river and wetland ecohydraulic studies (Birkhead *et al.*, 2007; Kleynhans *et al.*, 2007).

- River2D is a 2-D depth-averaged finite element hydrodynamic model that has been customised for fish habitat evaluation studies which was developed by the University of Alberta. The River2D model suite consists of four programs: R2D\_Bed (Steffler, 2002) for editing bed topography, R2D\_Ice (Blackburn and Unterschultz, 2002) for developing ice topographies to be use in the modelling of ice-covered domains, R2D\_Mesh (Waddle and Steffler, 2002) for developing computational meshes of the topographies and River2D (Steffler and Blackburn, 2002) which solves for the water depths and velocities throughout the meshes. River2D is then used to visualise and interpret the results and perform PHABSIM type fish habitat analysis.

The authors' recommended the above computational software because it provided greater access to a wider group of individuals as it is freeware and available on the internet for downloading.

Two-dimensional modelling is costly and time consuming (due to the additional field data requirements) and thus statistical frequency distributions of hydraulic parameters (velocity and/or depth) are applied to 1-D modelling to describe the spatial distribution characteristics of velocity and/or depth for the river reach. Various statistical frequency distribution methods for describing spatial distribution characters of different hydraulic variables exist. The review by Hirschowitz *et al.* (2007) included; *Depth Distribution* (Lamouroux, 1998), *Velocity Distribution* (Dingman, 1989; Lamouroux *et al.*, 1995; Azzelino and Vismara, 2001; Jonker *et al.*, 2002), *Velocity-Depth Distribution* (Stewardson and McMahon, 2002); and *Shear-Stress Distribution* (Lamouroux *et al.*, 1992).

Hirschowitz *et al.* (2007) proposed the methods of Dingman (1989) and Lamouroux *et al.* (1995) for use in ER studies for predicting characteristic depth-averaged velocity distributions and incorporated these methods into the HABitat FLOW Simulation Model (HABFLO). The probability distribution of velocity by Dingman (1989) is a power relationship and the form was confirmed for idealised, regular and irregular natural channels but the parameters could not be related to any measurable variables (Birkhead, 2010). Dingman (1989) suggested that the parameters are dependent on discharge and thus the relationship

is useful where measured velocities are available and its predictive ability at other flows is limited. The prediction of velocity distributions in reaches by Lamouroux *et al.* (1995) are related to simple descriptors of hydraulic variables (Froude Number, dominant roughness size ( $k$ ,  $m$ ), ratio of depth-averaged velocity to reach velocity, mean reach depth). The Lamouroux *et al.* (1995) model was found to give good predictions at a site scale and fair accuracy at a morphological scale (Hirschowitz *et al.*, 2007).

The HABitat FLOW Simulation Model (HABFLO) is a 1-D, uniform, steady ecohydraulic model that was developed by Hirschowitz *et al.* (2007). The model was designed to provide flow-dependent, ecologically relevant hydraulic information for all levels of ERs requiring site-specific data (Birkhead, 2010). HABFLO automatically predicts habitat type abundance and composition for fish and macroinvertebrates based upon the habitat flow classes specified by the ecologist (Section 2.4.1). HABFLO is based on three assumptions:

- Cross-sectional profiles and 1-D hydraulic parameters may be used to characterise the bed topography and hydraulic conditions, respectively, in morphological units.
- Frequency-distributions of depth-averaged velocity may be estimated with reasonable accuracy using statistical methods.
- Depth-averaged velocity, flow depth, and substrate type are mutually exclusive (independent) variables.

## **2.4 Describing Hydraulic Habitat**

The understanding of why and where organisms prefer to live is defined by ecologists in terms of the hydraulic nature of the physical habitat. Once there is an understanding of the hydraulic conditions that are optimal for different species or communities (Paxton *et al.*, 2010), the habitat requirements for biota may be specified in terms of hydraulic habitat. Hydraulic habitats are often defined as abiotic (physical and chemical) environmental features that are necessary for the survival and persistence of individuals and communities (Armstrong *et al.* 2003; Rosenfield, 2003). Several methods of quantifying hydraulic habitats are discussed below.

### **2.4.1 Flow Classes**

Biota in the aquatic environment are associated with a combination of hydraulic variables (e.g. depth and velocity) as well as substrate, vegetation and cover for fish. Flow classes are a means of grouping these combinations into units which have ecological meaning, in that they represent broad, known (or 'judged') preference of biota for hydraulic and biophysical variables. Flow classes do not necessarily represent suitability criteria (refer to discussion in Section 2.4.2) (Birkhead, 2010).

Flow Classes were initially developed by Oswood and Barber (1982) and adapted in SA for fish by Kleynhans (1999) and Jordanova *et al.* (2004) and for macroinvertebrates by Hirschowitz *et al.* (2007). The hydraulic variables used to specify fish flow classes are depth-averaged velocity and depth and macroinvertebrate flow classes are depth-averaged velocity, depth and substrate. The current flow classes used in SA are illustrated in Figure 2-5. Velocity-depth flow classes have also been used by Norwegian consultants for EF studies in Costa Rica (Laporte *et al.*, 2006). Computer Aided Simulation Model for Instream Flow Requirements (CASiMiR - Schneider, 2010) is a simulation model that applies expert knowledge through rule-based models to describe the types of habitats using physical and biological parameters. The rule-based models are based upon depth-velocity-substrate classes (Jorde *et al.*, 2000; Schneider *et al.*, 2001).

### **2.4.2 Habitat Suitability Criteria**

Habitat Suitability Criteria (HSC) or Weighted Usable Area (WUA) translates the collected hydraulic and geomorphological data on habitat into quantitative indices of habitat quality for the target species (Bovee, 1986). HSC and WUA are part of the IFIM/PHABSIM models (Section 2.1.3) and quantifying them entails collecting data on depth, velocity and substratum particle size wherever a species of interest is found in the study river, and using these to create HSC that together describe the most commonly-used hydraulic habitat conditions for the species. The hydraulic model predicts the values of point habitat variables (velocity, depth, particle size) for the discharge in a stream reach. HSCs are used to calculate values for each combination of point habitat variables. Their product is a habitat value (HV, ranging between 0 and 1), and when summed over the reach surface area, HV gives the

WUA. WUA can be simulated over a range of flows to give reach-scale relationships between WUA and discharge with the maximum curvature point/s indicating the critical discharge/s where large changes in habitat occur (Figure 2-6).

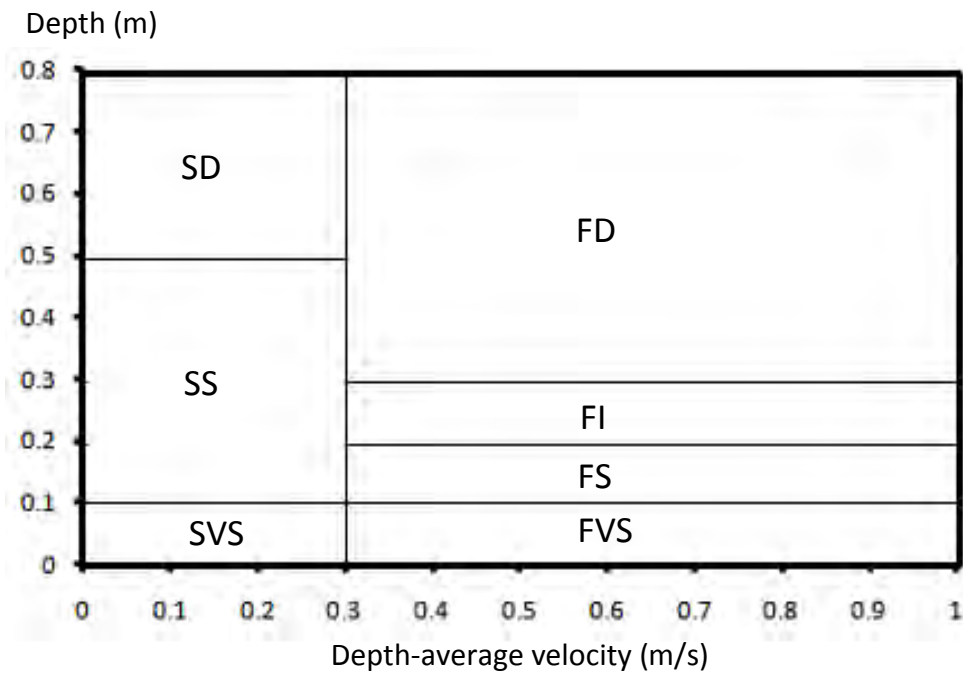
HSC targets individual species and are data- and time-intensive (King and Tharme, 1994). Lamouroux and Capra (2002) proposed a model to reduce habitat survey efforts but still retain much of the predictive power of the habitat-based models. The model uses simplified reach descriptions such as depth- and width-discharge relationships, particle size, and median flow.

In Canada, depth is used to identify habitat preferences. Depth and depth by habitat type metrics are calculated as percentages of total transect points for a station meeting specific criteria for a given flow. These values are then presented as a proportion of the total usable area. Hydraulic head is specified (in mm) to discriminate pool from non-pool habitats (Schroeter *et al.*, 2004).

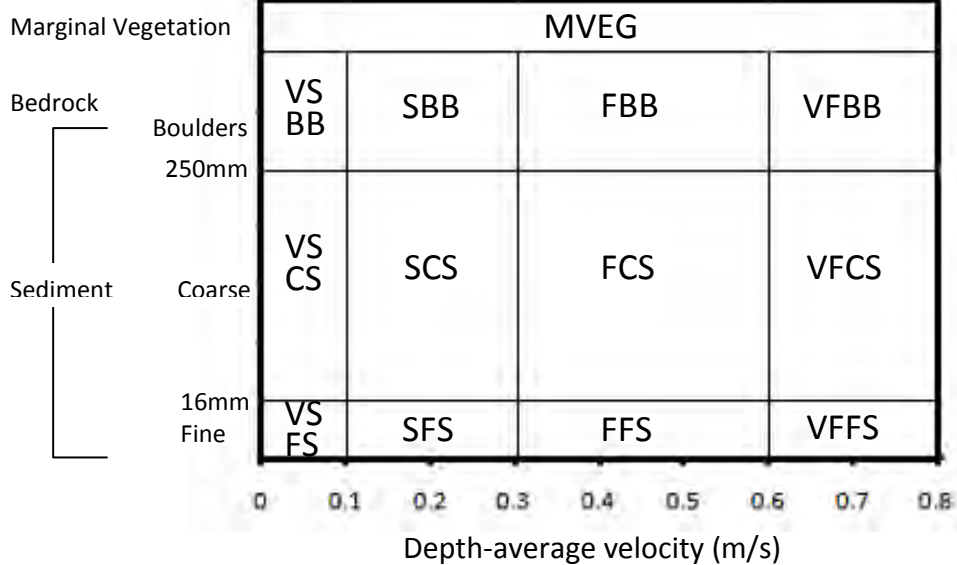
### **2.4.3 Hydraulic Biotopes and Functional Habitats**

The concept of hydraulic biotopes emerged during the mid 1990s (Newson *et al.*, 1998). Hydraulic biotopes and functional habitats are visual observations of surface flow behaviour which are thought to reflect combinations of sedimentology, depth, cover and velocity associated with the organisation of river bedforms and morphologies (Jowett, 1993; Wadeson, 1994). Habitats are represented in a spatial context that could then link to the observed distribution of organisms within a river reach, for given discharge values. The hydraulic biotope concept has been developed in SA by geomorphologists (Rowntree and Wadeson, 1999 and Wadeson and Rowntree, 2001) and by ecologists (King *et al.*, 1996; Pollard, 2000 and King and Shael, 2001).

Birkhead (2010) notes that this approach may suffer from the same scale limitations as the use of the Froude and Reynolds numbers for hydraulic characterisation. He further states that the occurrence and change of biotope with varying discharge is difficult to predict without 2-D deterministic modelling and the 2-D modelling will make the biotope description superfluous.

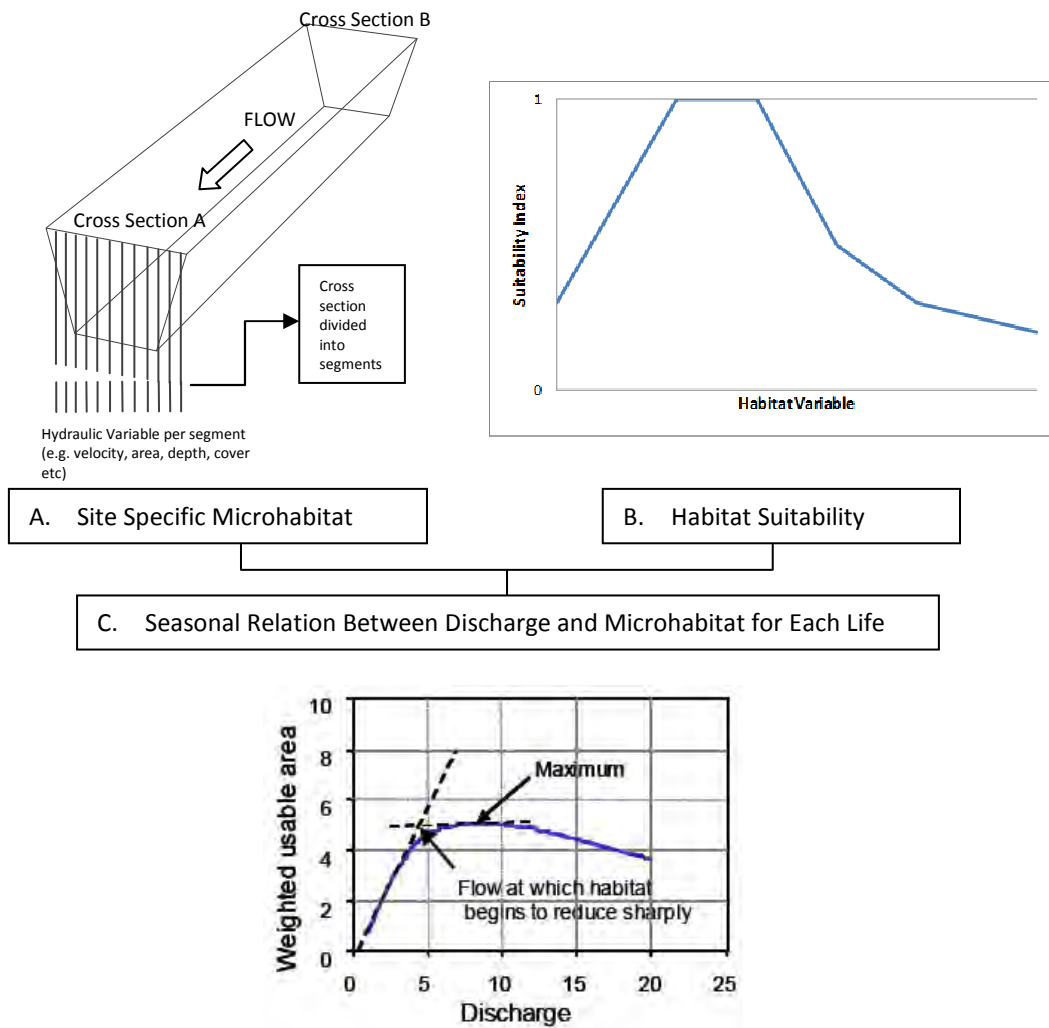


Habitable  
Surfaces



Note: SVS=slow/very shallow; SS=slow/shallow; SD=slow/deep; FVS= fast/very shallow; FS=fast/shallow; FI= fast/intermediate; FD=fast/deep; VSFS=very slow/fine sediment; SFS=slow/fine sediment; FFS=fast/fine sediment; VFFS=very fast/fine sediment; VSCS=very slow/coarse sediment; SCS=slow/coarse sediment; FCS=fast/coarse sediment; VFCS=very fast/coarse sediment; VSBB=very slow/boulder and bedrock; SBB=slow/boulder and bedrock; FBB=fast/ boulder and bedrock; VFBB=very fast/ boulder and bedrock; MVEG=marginal vegetation

**Figure 2-5 (TOP) Flow classes for fish (or velocity-depth classes), modified from Jordanova *et al.* (2004). (BOTTOM) Flow classes for macroinvertebrates, modified from Hirschowitz *et al.* (2007) [The velocity and depth axes are truncated for plotting purposes] (after Birkhead, 2010)**



**Figure 2-6 Habitat Suitability Criteria and Weighted Usable Area, adapted from Waddle (2001) and Beca (2008)**

## 2.5 Ecohydraulic Field Data and Outputs in South Africa

Birkhead (1999) and Rowston *et al.* (2008) describe the minimum and ideal (field) data required to undertake a hydraulic analysis for the holistic BBM method. The requirements for the other Southern African holistic methods, DRIFT and HFS-R, are mostly similar. The basic hydraulic field data for any ER assessment requiring explicit hydraulic information include the following:

- **Topographical cross-sectional survey**

Sites are selected that will result in critical hydraulic conditions (and hence are expected to be the most ecologically sensitive). A cross-section within the site is surveyed normal to the direction of flow. These critical sites are usually characterised by an increase in local channel gradient and occur in rapid and riffle geomorphological units.

- **Flow rate**

Flow rates are obtained using the velocity-area method or from flow gauges (including rated sections). The velocity-area method is the most commonly used manual technique for determining discharge in ungauged rivers in SA.

- **Low flow measured rating (i.e. average flow depth and discharge)**

The low-flow measurement is essential as a calibration point because of the difficulties associated with modelling low flows. The uncertainties associated with defining low flow resistance coefficients are specifically challenging. High flows can generally be modelled more accurately than low flows in rivers with large scale roughness, which are typical of EF sites.

- **Water surface gradients**

Water surface gradients are surveyed for the morphological unit, these represent the energy gradient and are equal to the bed gradient in uniform conditions. Water surface gradients are also surveyed for the site i.e. over a longer distance and includes the morphological unit and are generally used for the high flow rating point/s.

- **Spatial distributions of depth and depth-averaged velocity**

In the case of 1-D modelling, this information is determined using statistical frequency distributions:

- Additional information may be required for the frequency distributions (e.g. dominant roughness ( $k$ ) for use in the Lamouroux *et al.* (1995) velocity distribution model – Section 2.3.2).

- **Proportional substrate composition for determining flow classes**

The inundated depth and the corresponding percentage of fines and coarse sediment for the geomorphological unit is recorded.

- **Position and height of marginal vegetation relative to the river topography is surveyed.**

In addition to the field data listed above, the following requirements are also needed for the ecohydraulic model (HABFLO):

- **Rating coefficients (Equation 2-6)**

These may be computed directly from two rating points assuming the depth of zero discharge ( $c$ ) is equal to zero (i.e. Rapid III-type analysis). Alternatively non-linear (power) relationships may be fitted to the data, generally 3 or more data points, to obtain the coefficients.

- **Resistance coefficients (Section 2.2.1)**

Manning's  $n$  coefficient or other – The Manning formula (Equation 2-2) is predominantly used as the resistance equation in ecohydraulic modelling and for the entire range of flow depths, with calibrated low flow resistances obtained through field measurements.

- **Flow classes (Section 2.4.1)**

Numerical ranges of hydraulic variables defining fish (depth and velocity) and invertebrate (velocity and substrate) flow classes.

From a hydraulics perspective, the main difference between Rapid III, Intermediate and Comprehensive ER levels is the amount of hydraulic and habitat data collected at sites. Additional information and more rigorous hydraulic analyses may be appropriate for more detailed studies (i.e. Intermediate and Comprehensive). Table 2-5 lists the specific data requirements and methods of hydraulic analysis appropriate for the different ER levels.

The most basic description of river hydraulics is the stage-discharge relationship at a particular cross-section. For the purposes of this thesis, it is considered to consist of the relationship between discharge and water level (or stage), Equation 2-6 (Birkhead and James, 1998)

$$y = aQ^b + c \quad 2-6$$

where  $y$  flow depth (m),  
 $Q$  discharge ( $\text{m}^3 \text{s}^{-1}$ ), and  
 $a, b$  and  $c$  coefficients generally determined by regression.

The constant  $c$  has hydraulic meaning and represents the depth at zero discharge, or the ‘pooled’ water remaining in the river due to downstream structural controls, when flow ceases. A graphical representation of the relationship is illustrated in Figure 2-7.

The rating curve is best modelled by empirical correlation of measured data, when sufficient field data exists, requiring only measurements of water level and discharge and no physical description of the site. Although this is desirable, in terms of accuracy, it is seldom the case in ER studies, even at the Comprehensive level. Generally, extrapolation beyond the limits of measured rating data is necessary (Birkhead, 2010).

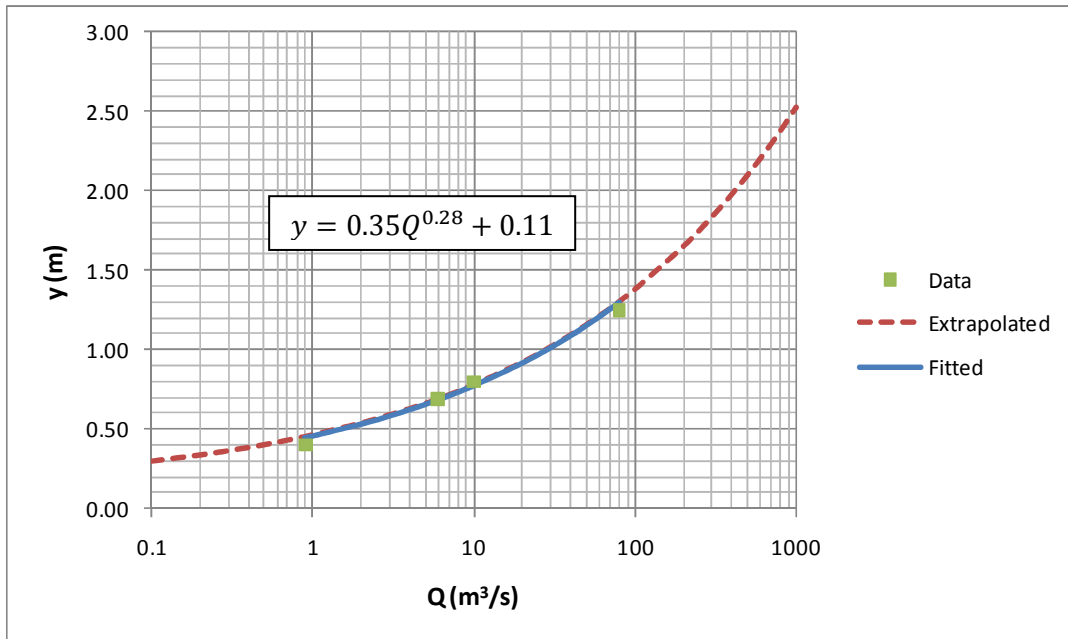
Uniform flow is generally assumed (i.e. equal longitudinal energy, water surface and channel bed gradients), and a resistance equation (e.g. Manning, Chezy or Darcy-Weisbach – Equations 2-2 to 2-4) is typically used to synthesise additional rating points for high flows using the hydraulic models discussed in Section 2.3.2. Sites should be selected and cross-sections located to support, as far as possible, the uniform flow assumption (i.e. a roughly constant water surface slope, and average cross-channel depth and velocity over the length of the morphological unit of interest). Measured and modelled rating points are used to model a continuous rating function. The rating function and cross-sectional geometry are then used to predict the relationships between discharge and ecologically important hydraulic parameters, including flow depth (maximum and average), average velocity, inundated channel width and wetted perimeter (Birkhead, 2010). Statistical frequency

distributions are then applied to the results to produce flow classes for fish and macroinvertebrates.

**Table 2-5 Data Requirement and Methods of Hydraulic Analysis Appropriate to Different Reserve Levels (after Birkhead, 2010)**

Reserve Level	Data Requirements		Methods of Analysis	
	Topographic and Hydraulic	Habitat Hydraulics	Hydraulic	Habitat Hydraulics
<b>Comprehensive</b>	<u>Surveys (4)</u> Cross-section(s) and/or 3-D bed topography; and water surface profiles; and 1:50 000 scale topographical valley slope <u>Discharge Measurements (4)</u> Velocity-area method; or gauge (including rated section)	<u>Spatial Distribution</u> Composition of substrate-types; position of marginal vegetation, depth and depth-average velocity	1-D (uniform or non-uniform); or 2-D	Statistical or spatially explicit depth-average velocity distributions
<b>Intermediate</b>	<u>Surveys (2)</u> Cross-section(s); and water surface profiles; and 1:50 000 scale topographical valley slope <u>Discharge Measurements (4)</u> Velocity-area method; or gauge (including rated section)	<u>Spatial Distribution</u> Composition of substrate-types; position of marginal vegetation, depth and depth-average velocity	1-D (uniform or non-uniform)	Statistical depth-average velocity distributions
<b>Rapid III</b>	<u>Surveys (1)</u> Cross-section; and water surface profiles; and 1:50 000 scale topographical valley slope <u>Discharge Measurements (4)</u> Velocity-area method; or gauge (including rated section)	<u>Spatial Distribution</u> Composition of substrate-types; position of marginal vegetation, depth and depth-average velocity	1-D uniform	Statistical depth-average velocity distributions

Shaded row (Rapid III) denotes basic hydraulic information and analyses.



**Figure 2-7** Example of a rating curve developed using measured and synthesised (extrapolated) data points and plotted on log-normal axes. Discharge is plotted against maximum depth (after James, 2010)

Results are generally provided as look-up tables (Table 2-6) relating discharge to ecologically relevant hydraulic parameters; maximum and average depth, width, perimeter, average and maximum velocity (based on the percentage point specified for the Lamouroux *et al.*, 1995 probability density function distribution), as well as the relative spatial composition of hydraulic/biophysical conditions defined using flow classes for fish and macroinvertebrates (Figures 2.4 and 2.5). Other results include modelled (and measured if available) frequency distributions of depth and velocity as functions of discharge and a resistance computation file (Tables 2-6 and 2-7). The resistance computation file contains the hydraulic conditions modelled at specified flow depth intervals and includes, Manning resistance at zero flow -  $n(0)$ , discharge ( $Q$ ), Manning  $n$  resistance coefficient ( $n$ ), energy gradient ( $S$ ), inundated cross-sectional area ( $A$ ), wetted perimeter ( $P$ ) and the discharge-depth relationship used at each flow depth interval ( $Q$ - $y$ ). The  $Q$ - $y$  relationship may be determined using (i) the rating function (indicated as 'Rat' in Table 2-7 - Equation 2-6) or (ii) Manning's resistance equation (indicated as 'Resist' in Table 2-7 - Equation 2-2). The difference between Rapid III, Intermediate and Comprehensive hydraulic results is essentially the level of uncertainty present in the field data and modelling, with comprehensive studies generally giving higher confidence results.

**Table 2-6 Modelled Hydraulic Data and Flow Classes Using Basic Hydraulic Analyses Indicated in Table 2-5 (after Birkhead, 2010)**

Hydraulic Variables							Flow Classes (% Spatial Composition)																			
Max Depth (m)	Ave. Depth (m)	Discharge (m <sup>3</sup> /s)	Width (m)	Perimeter (m)	Velocity (m/s)		Fish Velocity-Depth Classes							Invertebrates Velocity-Substrate Classes												
					Ave.	Max	SVS	SS	SD	FVS	FS	FI	FD	VSFS	SFS	FFS	VFFS	VSCS	SCS	FCS	VFCS	VSBB	SBB	FBB	VFBB	MVEG
0.02	0.01	0.000	0.1	0.1	0.03	0.09	100	0	0	0	0	0	0	10	0	0	0	5	0	0	0	0	0.02	0.01	0.000	0.1
0.04	0.02	0.000	0.2	0.2	0.04	0.15	100	0	0	0	0	0	0	9	1	0	0	4	1	0	0	0	0.04	0.02	0.000	0.2
0.06	0.03	0.001	0.3	0.3	0.06	0.21	100	0	0	0	0	0	0	8	2	0	0	4	1	0	0	0	0.06	0.03	0.001	0.3
0.08	0.04	0.001	0.4	0.4	0.07	0.26	99	0	0	1	0	0	0	7	3	0	0	4	1	0	0	0	0.08	0.04	0.001	0.4
0.10	0.03	0.002	1.2	1.3	0.06	0.21	100	0	0	0	0	0	0	8	2	0	0	4	1	0	0	0	0.10	0.03	0.002	1.2
0.12	0.05	0.006	1.3	1.4	0.09	0.32	89	8	0	3	0	0	0	6	4	0	0	3	2	0	0	0	0.12	0.05	0.006	1.3
0.14	0.06	0.011	1.4	1.5	0.12	0.41	79	14	0	6	1	0	1	5	4	1	0	2	2	0	0	0	0.14	0.06	0.011	1.4
0.16	0.08	0.017	1.4	1.5	0.15	0.52	70	18	0	10	3	0	3	4	5	1	0	2	2	1	0	0	0.16	0.08	0.017	1.4
0.18	0.10	0.026	1.5	1.6	0.18	0.60	61	22	0	13	5	0	5	4	5	1	0	2	2	1	0	0	0.18	0.10	0.026	1.5
0.20	0.11	0.037	1.6	1.7	0.21	0.69	15	61	0	5	19	0	19	3	4	2	0	2	2	1	0	0	0.20	0.11	0.037	1.6
0.22	0.12	0.049	1.7	1.9	0.24	0.78	17	52	0	8	24	0	24	3	4	3	1	1	2	1	0	0	0.22	0.12	0.049	1.7
0.24	0.13	0.065	1.9	2.1	0.27	0.85	18	45	0	10	27	0	27	3	4	3	1	1	2	1	0	0	0.24	0.13	0.065	1.9
0.26	0.14	0.086	2.1	2.4	0.30	0.97	17	38	0	14	31	0	31	2	3	3	1	1	2	2	1	0	0.26	0.14	0.086	2.1
0.28	0.15	0.115	2.2	2.5	0.35	1.07	16	33	0	17	35	0	35	2	3	4	1	1	2	2	1	0	0.28	0.15	0.115	2.2
0.30	0.16	0.152	2.4	2.7	0.41	1.22	13	27	0	20	39	0	39	1	3	4	2	1	1	2	1	0	0.30	0.16	0.152	2.4
0.32	0.16	0.194	2.7	3.0	0.46	1.34	12	23	0	22	41	2	41	1	2	4	3	1	1	2	1	0	0.32	0.16	0.194	2.7
0.34	0.16	0.249	3.1	3.4	0.52	1.48	11	19	0	26	39	5	39	1	2	3	4	1	1	2	2	0	0.34	0.16	0.249	3.1
0.36	0.15	0.321	3.6	4.1	0.59	1.56	11	15	0	31	37	6	37	1	2	3	4	0	1	1	2	0	0.36	0.15	0.321	3.6
0.38	0.15	0.431	4.2	4.7	0.69	1.68	9	11	0	37	31	12	31	1	1	3	5	0	1	1	3	0	0.38	0.15	0.431	4.2
0.40	0.15	0.535	4.9	5.5	0.75	1.73	9	9	0	41	21	20	21	1	1	2	6	0	1	1	3	0	0.40	0.15	0.535	4.9
0.42	0.15	0.657	5.3	6.0	0.80	1.85	8	8	0	42	21	21	21	1	1	2	6	0	1	1	3	0	0.42	0.15	0.657	5.3
0.44	0.16	0.799	5.7	6.4	0.86	1.99	7	7	0	42	24	20	24	0	1	2	7	0	0	1	3	0	0.44	0.16	0.799	5.7
0.46	0.17	0.964	6.0	6.7	0.92	2.04	5	8	0	34	32	21	32	0	1	2	7	0	0	1	4	0	0.46	0.17	0.964	6.0
0.48	0.19	1.154	6.3	7.1	0.99	2.12	4	8	0	28	39	21	39	0	1	2	7	0	0	1	4	0	0.48	0.19	1.154	6.3
0.50	0.20	1.371	6.5	7.4	1.06	2.29	3	8	0	22	46	22	46	0	1	1	8	0	0	1	4	0	0.50	0.20	1.371	6.5

**Table 2-7 Example of HABFLO Output – Resistance Computation File**

n(0):		0.3003				
Ave. Depth (m)	Discharge (m <sup>3</sup> /s)	Manning Coefficient (n)	Energy Slope (S)	Area (A)	Wetted Perimeter (P)	Discharge- Depth Relationship (Q-y)
0.02	0.000	0.288	0.030	0.000	0.110	Resist
0.04	0.000	0.276	0.030	0.000	0.220	Resist
0.06	0.001	0.263	0.030	0.010	0.330	Resist
0.08	0.001	0.251	0.030	0.020	0.440	Resist
0.10	0.002	0.238	0.030	0.030	1.310	Resist
0.12	0.006	0.226	0.030	0.060	1.380	Resist
0.14	0.011	0.214	0.030	0.090	1.460	Resist
0.16	0.017	0.201	0.030	0.110	1.540	Resist
0.18	0.026	0.189	0.030	0.140	1.610	Resist
0.20	0.037	0.176	0.030	0.170	1.700	Resist
0.22	0.049	0.164	0.030	0.210	1.930	Resist
0.24	0.065	0.152	0.030	0.240	2.150	Resist
0.26	0.086	0.139	0.030	0.280	2.360	Resist
0.28	0.115	0.127	0.030	0.330	2.510	Resist
0.30	0.152	0.115	0.030	0.370	2.680	Resist
0.32	0.194	0.102	0.030	0.420	3.010	Resist
0.34	0.249	0.090	0.030	0.480	3.450	Resist
0.36	0.321	0.077	0.030	0.550	4.050	Resist
0.38	0.431	0.065	0.030	0.620	4.740	Rat
0.40	0.535	0.060	0.030	0.720	5.460	Rat
0.42	0.657	0.057	0.030	0.820	5.960	Rat
0.44	0.799	0.055	0.030	0.930	6.420	Rat
0.46	0.964	0.054	0.030	1.050	6.740	Rat
0.48	1.154	0.053	0.030	1.170	7.080	Rat
0.50	1.371	0.051	0.030	1.300	7.420	Rat

## 2.6 Estimation of Hydraulic Parameters

Rapid III, Intermediate and Comprehensive ER studies involve field data collection for use in the ecohydraulic modelling. The data required to carry out the hydraulic analysis (Section 2.5) are not available in a desktop study because no field visits are undertaken. Thus, this information needs to be estimated using alternative methods. A representative cross-sectional profile and rating curve need to be estimated in order to carry out the desktop hydraulic analysis. The estimation of the cross-sectional profile and rating curve will require the use of several estimated hydraulic parameters. A literature review of hydraulic

parameter estimations was undertaken, noting that the objective was to estimate the hydraulic parameters using relationships with other more readily available data.

A large number of research topics related to hydraulic parameter estimations were found but only the research used in the development of the hydraulic sub-model are discussed below. The information was presented here so that it can serve as references when used in the later chapters.

### 2.6.1 Open Channel Flow Width and Flow Depth

Leopold and Maddock (1953) described the concept of hydraulic geometry, expressing the hydraulic relationships for a channel in the form of power functions of discharge as:

$$W = aQ^b, y = cQ^f, V = kQ^m \quad 2-7$$

where  $W$  Channel width,  
 $y$  Flow depth (average),  
 $V$  Flow velocity (average),  
 $Q$  Discharge,  
 $b, f, m$  are exponents,  
 $a, c, k$  scale factors, and

$$ack = 1 \text{ and } b + f + m = 1 \quad 2-8$$

The exponents represent the rate of change of the hydraulic variables as discharge changes and the scale factors define the values of the hydraulic variables when  $Q = 1$ . These hydraulic geometry equations have been developed for alluvial systems with the assumption that the river flow is steady and uniform and that the river tends to attain a state of equilibrium or quasi-equilibrium. Leopold and Maddock (1953) developed the relationships (Equations 2.7 and 2.8) for two types of hydraulic geometry:

1. *At-a-station/site*, where hydraulic parameters are obtained for a range of discharges at a specified cross-sections.
2. *Downstream*, where hydraulic parameters are obtained at several cross-sections downstream for a specific characteristic discharge.

They noted that the unit-sum constraint (Equation 2-8) holds for both at-a-station/site and downstream situations. Leopold and Maddock (1953) reported the following values for the exponents for USA rivers:

- At-a-Station :  $b = 0.26, f = 0.40, m = 0.34$
- Downstream :  $b = 0.50, f = 0.40, m = 0.10$

Parker (1979) has stated that the scale factors ( $a, c, k$ ) vary from locality to locality but the exponents ( $b, f, m$ ) exhibit a remarkable degree of consistency. However, Knighton (1974) emphasised variations in exponents as opposed to mean values and Rhodes (1977, 1978) noted that the exponent values for high flow conditions can be vastly different from those for low flow conditions. This is evident in the range of exponents that have been calibrated for a range of environments, using both field observations and laboratory simulations. The minimum and maximum average exponent values from published literature are tabulated in Table 2-8.

**Table 2-8 Average Values of Exponents  $b, f, m$  in Equation 2.7 – compiled from Singh, 2003**

	At-a-Station		Downstream	
	Minimum	Maximum	Minimum	Maximum
<b>b</b>	0.03	0.8	-0.71	0.54
<b>f</b>	0.12	0.5	-0.10	0.91
<b>m</b>	-0.23	0.59	0.13	0.79

The variation in the exponents and coefficients of hydraulic geometry relationships (Equation 2-8) could be attributed to factors mentioned by Huang and Warner (1995). In their review of hydraulic geometry they found that, besides discharge, hydraulic geometry is also controlled by bank erodibility (e.g. Knighton, 1974), suspended sediment load (e.g. Leopold and Maddock, 1953), coarse bedload material characteristics (e.g. Wilcock, 1971), channel slope (e.g. Ponton, 1972; Nanson and Young, 1981) and channel roughness related to bank cohesiveness and vegetation (e.g. Nanson and Young, 1981; Richards, 1982).

Several studies have been undertaken to understand and substantiate the range of exponents and scaling factors of the hydraulic geometry equations by including factors such as; frequency of discharge (Stall and Fok, 1968); drainage area (Singh and Broeren, 1989

and McConkey and Singh, 1992); stream size (Thornes, 1970); land use (Lane and Foster, 1980); boundary conditions (Yu and Wolman, 1987 and Huang and Warner, 1995); channel patterns (Wolman and Brush, 1961 and Chitale 1970, 1973); or different equilibrium assumptions (Knighton, 1977 and Rhodes, 1978).

Singh (2003) provides a review of the multitude of approaches that have been employed for deriving functional relationships among the aforementioned hydraulic variables. The approaches are based upon the following theories: (1) regime theory, (2) power function theory, (3) tractive force theory and its variants - threshold channel theory and stability theory, (4) similarity theory, (5) hydrodynamic theory, (6) thermodynamic entropy theory, (7) energy-entropy theory, (8) minimum extremal theories (e.g., minimum channel mobility theory, minimum stream power theory, minimum energy degradation theory, minimum entropy production theory, and minimum variance theory), and (9) maximum extremal theories (maximum friction theory, maximum sediment discharge theory, maximum sediment discharge and Froude number theory, and maximum entropy theory). Singh (2003) concludes the review of hydraulic geometry by stating:

*“... although a number of theories of at-a-site and downstream hydraulic geometry have been developed, it is not clear how these theories compare. Comparison of these theories using the same data is lacking and should be pursued. Furthermore, it is also not clear which theory should be applied where and under what conditions? Despite all the work done and new theories developed during the past half a century, the classic work of Leopold and Maddock (1953) still remains the benchmark contribution. This then raises a question if real progress has indeed been achieved in the area of hydraulic geometry.”*

Beck and Basson (2003) developed regime equations applicable to South African rivers. This was achieved through the calibration of channel width and depth based on a large data set of South African rivers. The equations developed, for natural and impacted rivers, relate equilibrium width ( $W$ ) or depth ( $y$ ) to discharge with a return period of 10 years ( $Q_{10}$ ) and channel gradient ( $S$ ). The forms of the equations for natural channels are:

$$W \text{ or } y = aQ_{10}^b S^c$$

2-9

where  $a, b, c$  are coefficients.

## 2.6.2 Discharge

The relationships developed for estimating width, depth and velocity are dependent upon discharge (Section 2.6.1) and therefore a review of methods developed to estimate discharge was undertaken. Investigations into desktop type relationships and methods developed to determine the discharge in a river revealed two methods that are of significance for this thesis. These methods are (i) the use of statistical techniques to generate a discharge for a given return period and (ii) the use of satellite and digital elevation models to determine the discharge through remote sensing techniques. Techniques of satellite-derived estimates of hydraulic variables (e.g. discharge, width, area) are in their infancy but their application in ungauged basins appears feasible in the special case of braided rivers (Smith, 1997). However, braided sections are rarely selected for EF assessments as these sections require more rigorous ecohydraulic modelling.

- **Estimation of Discharge using Statistical Models**

For gauged catchments with long record periods (> 25 years), the statistical techniques of frequency analysis may be applied directly to determine the magnitude of any flood event with a specified return period or probability of exceedance (Chadwick and Morfett, 1998). Frequency analysis involves the use of instantaneous maximum recorded data and the application of flood frequency distribution models (e.g. Normal, Gumbel, Log Normal, Log – Pearson Type 3 etc).

Mkhandi and Kachroo (1997) regionalised the Southern Africa flood data (Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe) by grouping basins into homogeneous regions. Homogeneity implies that regions have similar flood generating mechanisms and thus a homogeneous region consists of sites having the same standardised frequency distribution form and parameters. The regionalisation was based on catchment boundaries, a topography

map, mean annual rainfall and location of gauging stations and, in the case of SA, a map defining maximum flood peak regions (Kovacs, 1988). A total of 13 regions were identified for SA (Figure 2-8 and Table 2-9). A regression analysis was subsequently done using the statistical distribution of flood flows for each region and relationships were developed for predicting mean annual flood in ungauged catchments. The relationship developed to predict mean annual flood are related to the catchment area and of the form:

$$\bar{Q} = x(CA)^y \quad 2-10$$

where  $\bar{Q}$  Mean annual flood ( $\text{m}^3 \text{s}^{-1}$ ),  
 $CA$  Catchment area ( $\text{km}^2$ ), and  
 $x, y$  Coefficients for each region (Table 2-9)

Mkhandi and Kachroo (1997) also presented flood frequency curves for the 13 South African regions (Figure 2-9) and noted a more-or-less linear relationship between floods up to return periods of approximately 10 years with the 10 year event being approximately 1.8 times the mean annual flood ( $\bar{Q}$ ) across all the regions in SA.

Researchers attempting to define the most important flows in controlling channel processes and channel form have introduced three types of discharges; Dominant Discharge, Bankfull Discharge and Effective Discharge. Dollar and Rowntree (2003) provide the following definitions for the three types of discharges:

- **Dominant Discharge** – was conceptualised as the constant flow rate that would produce the same channel morphology as would a sequence of naturally varying flows. The current accepted notion is that assigning a dominant discharge to a channel is an oversimplification because the channel morphology is made up of a number of components, each having its own response to variable flows and therefore its own dominant discharge (Prins and De Vries, 1971).

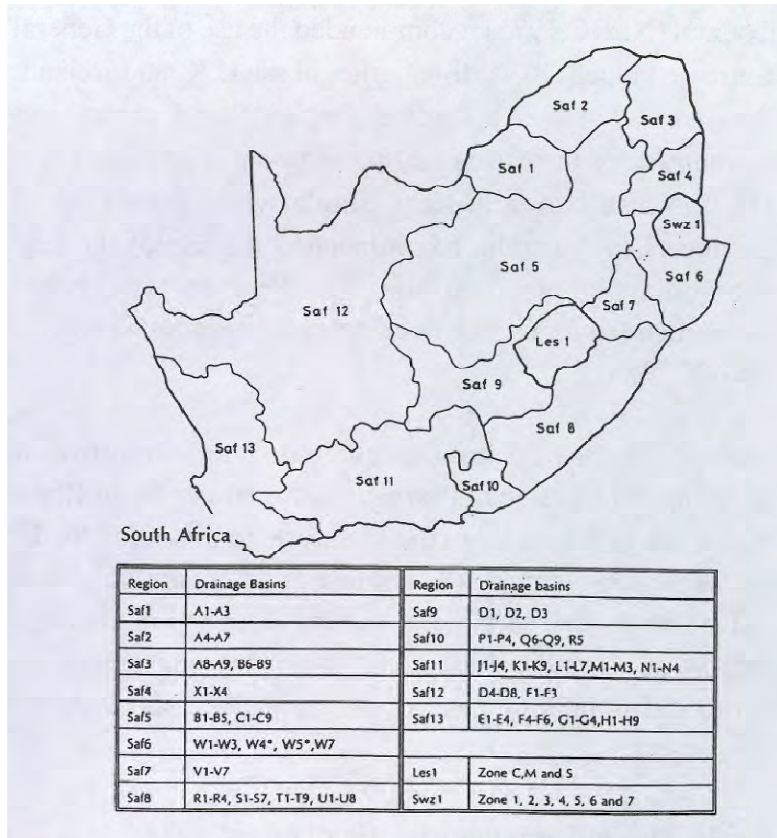


Figure 2-8 Delineated Hydrological Homogenous Regions for South Africa (after Mkhathi and Kachroo, 1997)

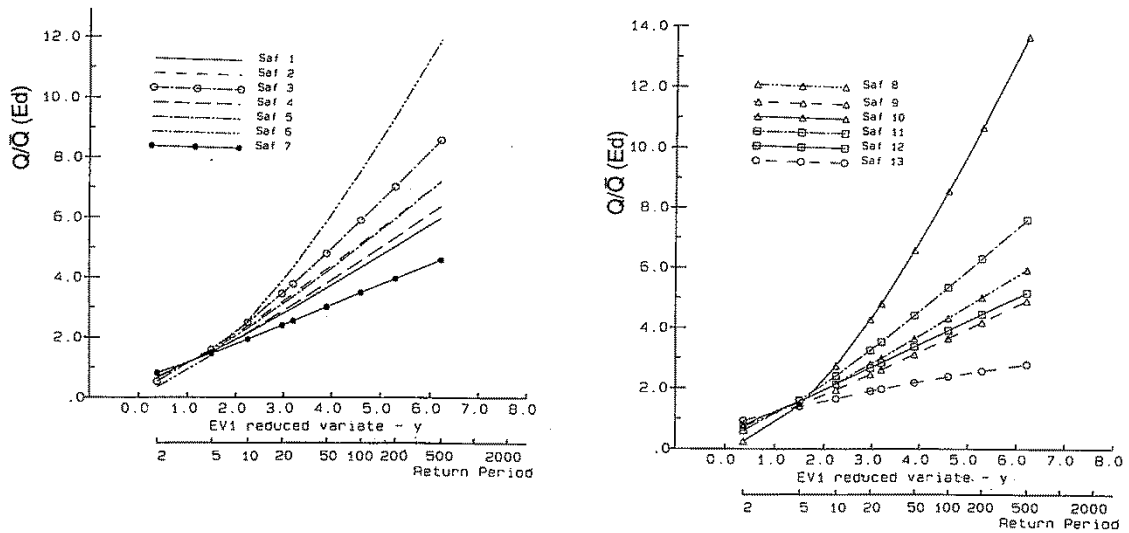


Figure 2-9 Flood Frequency Curves for 13 Regions in South Africa (after Mkhathi and Kachroo, 1997)

**Table 2-9 Coefficients for Mean Annual Flood (Equation 2.10) for South Africa (after Mkhandi and Kachroo, 1997)**

Region No.	Drainage Basin	x	y	Description
1	A1 to A3	1.920	0.579	South West Transvaal Bushveldt, North West Rand
2	A4 to A7	0.706	0.601	North West Transvaal Bushveldt
3	A8, A9, B6 to B9	10.629	0.354	North East Transvaal Bushveldt
4	X1 to X4	0.574	0.766	North of Eastern Lowveld, North of Drakensburg, South East Transvaal Bushveldt
5	B1 to B5, C1 to C9	5.342	0.445	South Transvaal Bushveldt, Highveld
6	W1 to W3, W4, W5, W7	0.544	0.903	Eastern Lowveld, Coastal Plain
7	V1 to V7	4.974	0.540	Eastern Lowveld, Central Drakensberg
8	R1 to R4, S1 to S7, T1 to T9, U1 to U8	2.835	0.618	Eastern Lowveld
9	D1 to D3	5.562	0.560	Southern Drakensberg, Southern Highveld
10	P1 to P4, Q6 to Q9, R5	7.924	0.426	Eastern Cape ranges
11	J1 to J4, K1 to K9, L1 to L7, M1 to M3, N1 to N4	7.450	0.407	Great Karoo, Eastern part of Cape ranges
12	D4 to D8, F1 to F3	2.234	0.518	Upper Karoo, Kalahari & Namib deserts
13	E1 to E4, F4 to F6, G1 to G4, H1 to H9	5.857	0.500	Western Cape ranges

- Bankfull Discharge** – is defined as the discharge which fills up the main channel, with further increase in discharge resulting in overflow onto the floodplain. UK and USA bankfull discharges have been determined to be associated with flow recurrence intervals between 1 and 2 years. Beck and Basson (2003) have found the South African river channels are formed by discharges that occur rather infrequently with recurrence intervals of between 5 and 20 years. Similarly, Dollar and Rowntree (2003) found that there appears to be no consistency in terms of the frequency of occurrence of bankfull discharge in three South African river systems (Mkomazi [return period between 1.5 and 2.44], Mhlatuze [return period between 1.8 and 3.4] and Olifants [return period between 1.6 and 9.5]).

- **Effective Discharge** – is defined as the discharge that transports the most sediment over time (Orndorf and Whiting, 1999). Wolman and Miller (1960) argued that moderate flows in a river system are more efficient at having an effect on the channel boundaries over time than are high, rare occurring or low, regularly occurring flows.

### 2.6.3 Cross-sectional Channel Shape

Hydraulic parameters are used to quantify the water needs of various biotic components. Some of these hydraulic parameters are calculated based upon the cross-sectional shape of the river. Reviews of the types of channel shapes that occur are discussed below.

A river balances and minimises its energy expenditure through adjustment of its channel cross-sectional shape. Along the length of a river, the cross-sectional shape adapts to the discharge and sediment load that is delivered to it (Mount, 1995).

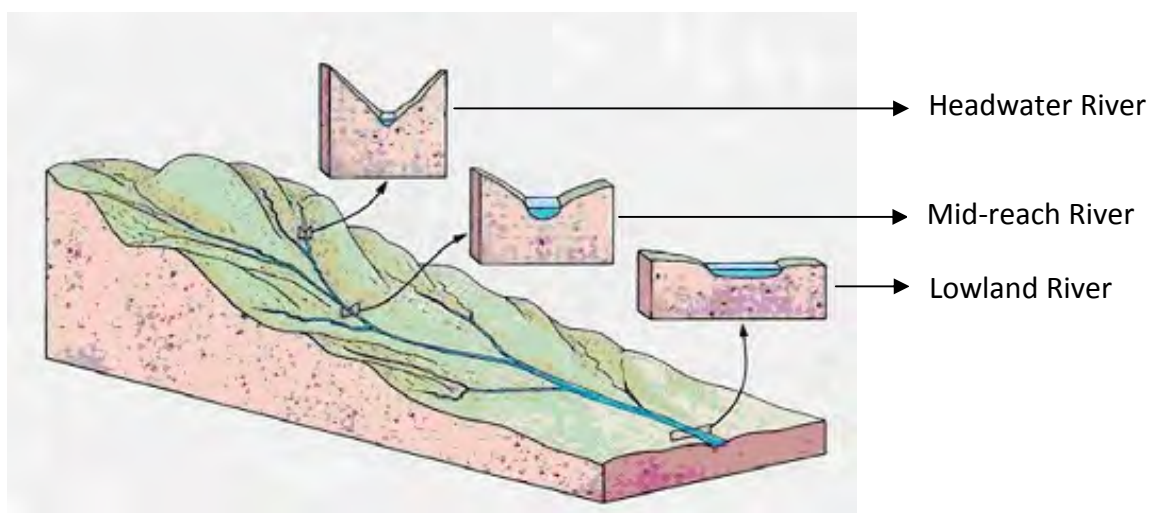
Generally, the geometry of a channel cross-section may be defined by several independent variables; semicircular sections are defined by one variable (i.e. depth); rectangular, triangular and parabolic sections are defined by two variables (i.e. depth and width); and trapezoids, round-bottom triangles and round-cornered rectangle sections are defined by three variables (i.e. depth, width and side slopes) (Chow, 1959).

A channel section will be most hydraulically efficient when the discharge for a given cross-sectional area is at a maximum (Chow, 1959); this is the concept of *best hydraulic section*. Semi-circular sections are the most efficient (Richards, 1982; Julien, 2002) but unconsolidated sediments cannot sustain this shape. Thus, semi-circular sections are not practical in natural rivers as they generally experience some degree of erosion.

The conventional method of establishing the best hydraulic section uses elimination and differentiation to arrive at a relationship between the independent variables of a cross-section. However, this method is unmanageable for complex natural cross-sections (Monadjemi, 1994). Using Lagrange's method of undetermined multipliers, Monadjemi

(1994) presented an alternative approach for determining the best hydraulic section for two and three independent variables. Monadjemi (1994) found that for a given flow and longitudinal gradient, the minimisation of cross-sectional area is shown to be mathematically equivalent to the minimisation of the wetted perimeter. The best hydraulic section was determined to be the round-bottom triangular section and is slightly more efficient than the widely used trapezoidal section.

Different channel shapes are observed in river reaches even though the discharge, resistance coefficient and longitudinal gradient are the same. The reason for the variation in channel shapes is due to sediment load of the river system. Mount (1995) states that channel cross-sections in suspended load-dominated rivers tend to be steep-walled and narrow while bedload-dominated rivers tend to be wider and shallower e.g. alluvium channels in equilibrium are approximately trapezoidal in shape (Barr *et al.*, 1980; Nishat, 1981; Kawas, 1985; Matin, 1988, 1996), mountain streams are generally approximated to be triangular (or V) shaped due to the steep gradients and great deal of abrasion. Figure 2-10 illustrates the channel cross-sectional shapes and sizes that are generally observed for headwater rivers, lowland rivers and rivers located in between the two (mid-reach rivers) (refer to Table 4-1 for river descriptions).



**Figure 2-10 Typical Channel Shape Types of River Sections Observed within a Catchment after Geocaching, 2011)**

Barnes (1967) and Hicks and Mason (1998) photographic matching guides include topographical surveys of river cross-sections. The publications were used to determine the

general shapes of natural channels. Rectangular, trapezoidal, parabolic and triangular (or V) shaped natural channels were observed in these two publications.

#### 2.6.4 Channel Bed Particle Size

The composition of the river bed material provides the physical living space (habitat) for organisms. Southwood (1988) describes the physical habitat as the ‘template on which evolution forges characteristic life-history strategies’ and it is thus important to predict channel bed particle sizes in order to represent these physical habitats. These physical habitats can be used to predict what types of organisms may potentially occur in the river system.

Hack (1957) undertook field observations in the Calfpasture River, which is a headwater stream of the James River in Virginia, USA. Hack (1957) observed that the size of the bed material remained essentially constant for a fairly long reach of river. The material size was not ordinarily affected by position in the channel with respect to pools and riffles. Although the local variations in bed material size are small, the overall change in bed material size in a single stream was found to be great. Hack (1957) identified a relationship between channel gradient and the ratio of the size of bed material to drainage area (Equation 2-11).

$$S_o = 18 \left( \frac{M}{DA} \right)^{0.6} \quad 2-11$$

where  $S_o$  Bed Gradient (ft mile<sup>-1</sup>),  
 $M$  Median particle size of the bed material (mm), and  
 $DA$  Drainage area (mile<sup>2</sup>)

The constant 18 is determined by the units of measurement used.

No limits have been specified for Equation 2-11, however a three-component diagram was provided by Hack (1957) that indicated a maximum drainage area of 1000 sq miles (i.e. 2590 km<sup>2</sup>).

Shields (1936) research in sediment transport showed that particle entrainment was related to a form of Reynolds Number. The relationship developed (Equation 2-12) is based on the

friction velocity,  $u_*$ . It is noted that ‘friction velocity’ is a ‘reference value’ and no such velocity exists in the flow.

$$Re_* = \rho u_* k / \mu \quad 2-12$$

where  $Re_*$  Shear Reynolds Number or Boundary Reynolds Number,  
 $\rho$  Density of the fluid ( $\text{kg.m}^{-3}$ ),  
 $k_s$  Nikuradse roughness (m),  
 $\mu$  Coefficient of absolute viscosity of a fluid ( $\text{N s/m}^2$  or  $\text{kg/m s}$ ), and  
 $u_*$  Shear velocity ( $= \sqrt{\frac{\tau_o}{\rho}}$ );  
 $\tau_o$  is the boundary shear stress ( $\text{N.m}^{-2}$ ), Equation 2-1

Shields proved that there is a well defined band of results indicating the threshold of motion and van Rijn (1984) expressed the Shields threshold as:

$$\frac{RS_o}{D} = 0.0924 \quad 2-13$$

where  $R$  Hydraulic radius (m), and  
 $S_o$  Energy gradient

Equation 2-13 may be used to estimate (a) the minimum stable particle size for a given channel or (b) the critical shear stress for a given particle size (Chadwick and Morfett, 1998).

Batalla *et al.* (2010) undertook field experiments and measurements of bed material entrainment and transport in the Ribera Salada River, Romania. They found a distinct sequence of sand and gravel mobility in the patches of fine sediments present in gravel-bed rivers. The sequence observed was:

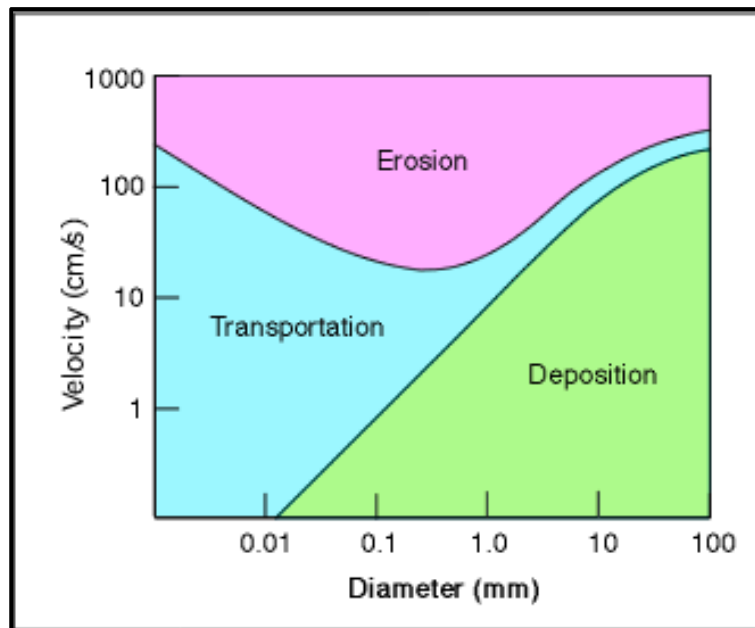
1. Once the bed-material begins to agitate, the sand particles move downstream independently of their relative size (i.e. the overpassing phase, see Ashworth and Ferguson, 1989).

2. When the sand from the patch is fully mobilized, gravel begins to agitate and is eventually transported, showing a distinct size-selective entrainment behaviour (the size-selective phase of Komar, 1996).

It is noted that the force they determined necessary to entrain fine and coarse sediment is much higher (5 times on average) than that predicted by the Shields relationship. The Shields' and Batalla *et al.* (2010) relationships cross over at a particle size of  $\approx 50\text{mm}$ , this is the point where mobility of gravels begins.

Church and Hassan (2005) and Batalla *et al.* (2010) report that particle sizes greater than 50mm would entrain at smaller forces than the Shields relationship predicts due to its relatively high exposure in the river bed. Wiberg and Smith (1987) showed that lower entrainment forces were required for particles at the surface of a poorly sorted bed when compared to the entrainment forces required on the same particles placed on a well-sorted bed consisting of uniform particle sizes. In general, on a non-uniform bed, larger particles of a size distribution are moved at forces that are lower than those required on a uniform bed, while the finer particles require greater forces to entrain.

The Hjulström's Diagram, originally published by Henning Filip Hjulström in his doctoral thesis (Hjulström, 1935), is a graph of sediment size (mm) and water velocity ( $\text{cm s}^{-1}$ ) indicating whether a river will erode, transport or deposit sediment (Figure 2-11). The Hjulstrom's Diagram plots two curves representing the minimum velocity required to erode sediments of varying sizes from the river bed (i.e. the entrainment threshold - Top Curve), and secondly, the minimum velocity required to continue to transport sediments of varying sizes (Bottom Curve). Hjulström's diagram is empirically developed based on the cross-sectional mean flow velocity, in a flow depth of at least 1m deep, required to initiate movement of equal size particles on a flat, uniform bed (Sinha, 1993).



**Figure 2-11 Hjulström Diagram – The diagram illustrates the relationships between equal size particles (diameter) and average velocity, indicating critical thresholds for particle erosion, transportation and deposition (after Columbia University, 2011)**

Characteristic discharges (dominant, bankfull or effective) have also been used to identify when sediment begins to entrain. Jonker *et al.* (2002) have shown that the geometry and localised particle size distribution characteristics of macro-scale bed-forms (e.g. pool-riffle structures) in cobble-bed rivers in the Western Cape display a good correlation with bed shear stresses during bankfull discharge, which has been linked to recurrence intervals of between 1 and 3 years. Pitlick and van Steeter (1998) found that effective discharges in the upper Colorado River are maintained from about half bankfull, with gravel entrainment initiated at this stage. Dollar and Rowntree (2003) determined the effective discharge for sand, gravel and cobbles for 3 SA river systems. They determined that the effective discharge that transports the most bed material over a long period of time to be in the 5% to 0.1% (Mkomazi) and 5% to 0.01% (Mhlatuze and Olifants) range on the daily FDC. Dollar and Rowntree (2003) confirmed that a greater proportion of the sand-fraction of the bed material is transported at low discharges.

## 2.7 Summary

Holistic EFAs consist of hydrological, ecological and hydraulic components with hydraulic analysis of flow in natural open channels found to be the crucial link between ecology and hydrology. Hydraulic field data are collected and used in ecohydraulic models to produce hydraulic habitats. These hydraulic habitats describe biotic habitat requirements that are necessary for the survival and persistence of the biota.

However, no field data are expected to be available for the desktop hydraulic sub-model and thus the ecohydraulic model input requirements need to be estimated. Literature reviews were undertaken to determine the various methods developed to estimate hydraulic parameters that could be used in the development of the hydraulic sub-model. The majority of the relationships to estimate hydraulic parameters discussed above are very specific to the conditions under which they were developed or have not been applied as a desktop approach to predict the shape of channels or hydraulic characteristics. The literature therefore does not provide a conclusive answer about whether a desktop approach to defining the channel shape and hydraulic characteristics is achievable. Consequently, no clear guidelines could be obtained about the type of data that should be collected to achieve the objective of developing a desktop hydraulic sub-model. The direct use of these relationships in the development of the hydraulic sub-model for the purposes of this study is therefore limited but the form of the relationships will be used as a guide in the estimation and development of the hydraulic sub-model parameters (Chapters 5 – 7).

### **3 BRIEF OVERVIEW OF THE REVISED DESKTOP RESERVE MODEL**

The Desktop Reserve Model (Hughes and Hannart, 2003) was developed to provide a method for generating quick, low confidence, initial estimates of the ERs. The ecological water requirements are modified hydrological flow regimes for the river, each linked to a predetermined objective in terms of the ecosystems' future condition. The DRM's relationships are primarily based on hydrology and implicitly incorporate hydrological-flow-ecological relationships.

The Revised Desktop Reserve Model (RDRM) aims to incorporate the recent developments (from past EWR studies) in flow-hydraulic-habitat-ecological methods and thus improve the confidence in desktop ER results. This is to be achieved through the development of a hydraulic sub-model, an ecological sub-model and revising the DRM (i.e. hydrological sub-model). The hydraulic sub-model will serve as the link between the hydrological and ecological sub-models. This thesis is a direct contribution to the development of the hydraulic sub-model and its integration into the RDRM.

This chapter of the thesis has been included to provide the context for the development of the hydraulic sub-model and because no formal publication of the Revised Desktop Reserve Model (RDRM) is currently available (the final report to the Water Research Commission is under review and expected to be published during 2012 – Hughes *et al.*, in press). The involvement of the author of this thesis was in the development of the concepts and the practical implementation of the hydraulic sub-model and the inclusion of this summary of the RDRM in the thesis is not designed to suggest that the author contributed to the development of the other sub-models, or their integration into the final version of the RDRM.

The RDRM is implemented as part of both the original Spatial and Time Series Information Modelling (SPATSIM) framework (Hughes and Forsyth, 2006; Hughes, 2004b) and the updated Spatial and Time Series Information Modelling – Hydrological Decision Support Framework (SPATSIM-HDSF - Clark *et al.*, 2009) and consists of 5 main components (Figure 3-1); the hydrological sub-model, the hydraulic 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 ER requirements as assurance rules or time series. For simplicity, the term SPATSIM is used to refer to the original SPATSIM framework and SPATSIM-HDSF.

The use of the RDRM will require an understanding of the basic functionality of running a SPATSIM application e.g. loading and adding attribute data, setting up models etc. The model is set up in exactly the same way as any other model in SPATSIM which involves associating attribute information contained within a SPATSIM application with the model input/output requirements. The SPATSIM input requirements for the RDRM consist of:

- **Site name** - a text attribute simply containing the name of the ER 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 DRM. The only parts of the data table that are used in the RDRM are the two parameters of the monthly baseflow separation method (Hughes *et al.*, 2003) which is used as part of the hydrology sub-model (the last two parameters in the list are referred to as 'BF Alpha' and 'BF Beta'). These are regionalized values associated with the implementation of the original DRM.
- **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 and the attribute is populated by importing the monthly flow data from text files.
- **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 and the attribute is populated by importing the monthly flow data from text files.
- **Regional Hydraulic Model Parameters** - an array attribute containing the parameters of the hydraulic sub-model. Most of the attributes can be populated from data generated when the hydraulic sub-model is run. However, four rows should be populated by editing the array data in SPATSIM. These are the Geo Zone (integer value between 1 and 6 representing Geomorphological Zones A to F), Flood Region (integer values between 1

and 13 – see Figure 2-8 and Table 2-9), Valley Slope (a fraction) and Catchment Area (km<sup>2</sup>). In the near future it is intended to incorporate a national database of values for the Geo Zones and Flood Region parameters, while Valley Slope will be computed using DEM and topographical maps in SPATSIM's GIS interface. Until these are prepared, the user will be required to use other sources of information as discussed in the preceding chapters. Table 2-9 can also be used to select the appropriate flood region.

- **Surveyed Channel Cross-Section and Rating Curve** - 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.

Before setting up a site in SPATSIM users should ensure that they have loaded (or edited) the data for the inputs discussed above. The output attributes are:

- **Total Flow Assurance Data** - an array attribute that is used for saving the total flow (low flows and high flows) ER assurance rules for a specific ER category.
- **Low Flow Assurance Data** - an array attribute that is used for saving the low flow (no high flows included) ER assurance rules for a specific ER category.
- **Total Reserve Requirement** - a time series attribute that is used to save the time series of ER 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 ER determination (which can also be saved to a text file during the running of the model).

Figure 3-1 illustrates the main screen of the RDRM and 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 the information required for the lower sub-models are generated by the steps in the preceding sub-model (Figure 1-2). Users are not able to run a sub-model before the others are completed, beginning with the hydrological sub-model. The 'tick' boxes to the right of each option indicate that the sub-model has been completed successfully and enables the user to readily see the progress in the running of the RDRM. However, it is possible to move around within the various steps to modify some of the results or to review some of the outputs.



**Figure 3-1 Main Screen of the RDRM**

The hydrological sub-model uses the *Single Parameter Data* and *Flow Data* inputs and a % point for the maximum baseflow on the baseflow duration curve, which is selected in the hydrology sub-model, to determine the dominant wet and dry season months as well as fixing the maximum low flow discharge. Two maximum low flow discharges are determined in the hydrological sub-model, (i) the mean monthly discharge (in  $\text{m}^3\text{s}^{-1}$ ) for the 75<sup>th</sup> percentile of the natural flow duration curve (FDC) based on total flows and (ii) the selected percentile from the natural FDC based on separated baseflows. The default percentile for the maximum baseflow is set to 20% and the default maximum low flow discharge used is the separated baseflow option. The selected maximum low flow discharge is used in the determination of the distribution of ecological habitats (flow classes, FC) using the hydraulic sub-model outputs and thereafter the stress-flow relationships in the ecological sub-model. Details of the hydraulic sub-model design and structure are provided in Chapter 4.

The approach used in the ecological sub-model is the synthesis of understanding developed by SA ecologists over the past two decades. However, only rheophilic fish guilds were incorporated into the ecological sub-model because the habitat requirement changes with flow for other fish guilds and other biota types (e.g. macro-invertebrates or riparian vegetation) were not available to the ecological sub-model development team in a format that matched the design of the model.

The ecological sub-model (Figure 3-2) uses the fish FCs (referred to as 'habitat classes' in Figure 3-2, top left) for the wet and dry months for all possible flow depths lower than the selected maximum low flow discharge. The use of these FCs is largely associated with the requirement for both large and small rheophilic fish guilds, which are flow sensitive and generally have the highest flow requirements. The FCs are determined using the output from the hydraulic sub-model (discussed later), to estimate the stress-flow relationships for both seasons (Hughes and Louw, 2010). The basis for estimating stress is the reduction in the frequencies of the Fast Shallow (FS), Fast Intermediate (FI) and Fast Deep (FD) FCs coupled with the assumption that an ecological stress index of zero is associated with the maximum low flow discharge (for a specific season) while zero flow represents a stress of 10. The natural and present baseflow time series are then processed through the stress-flow relationship to generate the natural, present day and several EWR category stress duration curves for the two seasons. Thereafter, FDCs are generated by processing the flow data through a combination of the stress duration curves and the stress-flow relationship. In the ecological sub-model, users are provided with some flexibility in the way in which the EWR category stress duration curves are related to the natural and present day stress duration curves. The principle of the flood requirement approach is to use a method similar to that used in the original DRM (Hughes and Hannart, 2003) to relate the annual high flow requirements to the calculated hydrological variability index. The majority of the RDRM is focused on improved methods of estimating the low-flow requirements and typically more accurate and realistic high flow requirements for the EWR are determined using alternative methods not included in the RDRM.

The stress frequency graphs in the lower part of Figure 3-2 include lines representing natural and present day conditions as well as estimates for the ecological protection

categories A, B, C and D. The default category lines are located using a rule-based system of shifting upwards (i.e. higher stress and lower flows) from the natural stress frequency curves. The rules have been established from experience based on the results from many previous EWR workshops (Hughes *et al.*, in press), however, the development of the ecological sub-model also needed to recognise that the present day flow regime and ecological stress characteristics are frequently taken into account during EWR workshops. Some of the 'user intervention options' (Figure 3-2) therefore allow for the stress frequency curves of one of the ecological categories to be aligned to the present day stress characteristics and the others adjusted accordingly. More details of the approach used within the ecological sub-model are contained within the final research report for the complete RDRM (Hughes *et al.*, in press). The main point that needs to be made for the purposes of this study is that assessments of the outputs of the hydraulic sub-model (Chapter 8) against previous workshop results may need to allow for the way in which the present day situation was accounted for in the workshops.

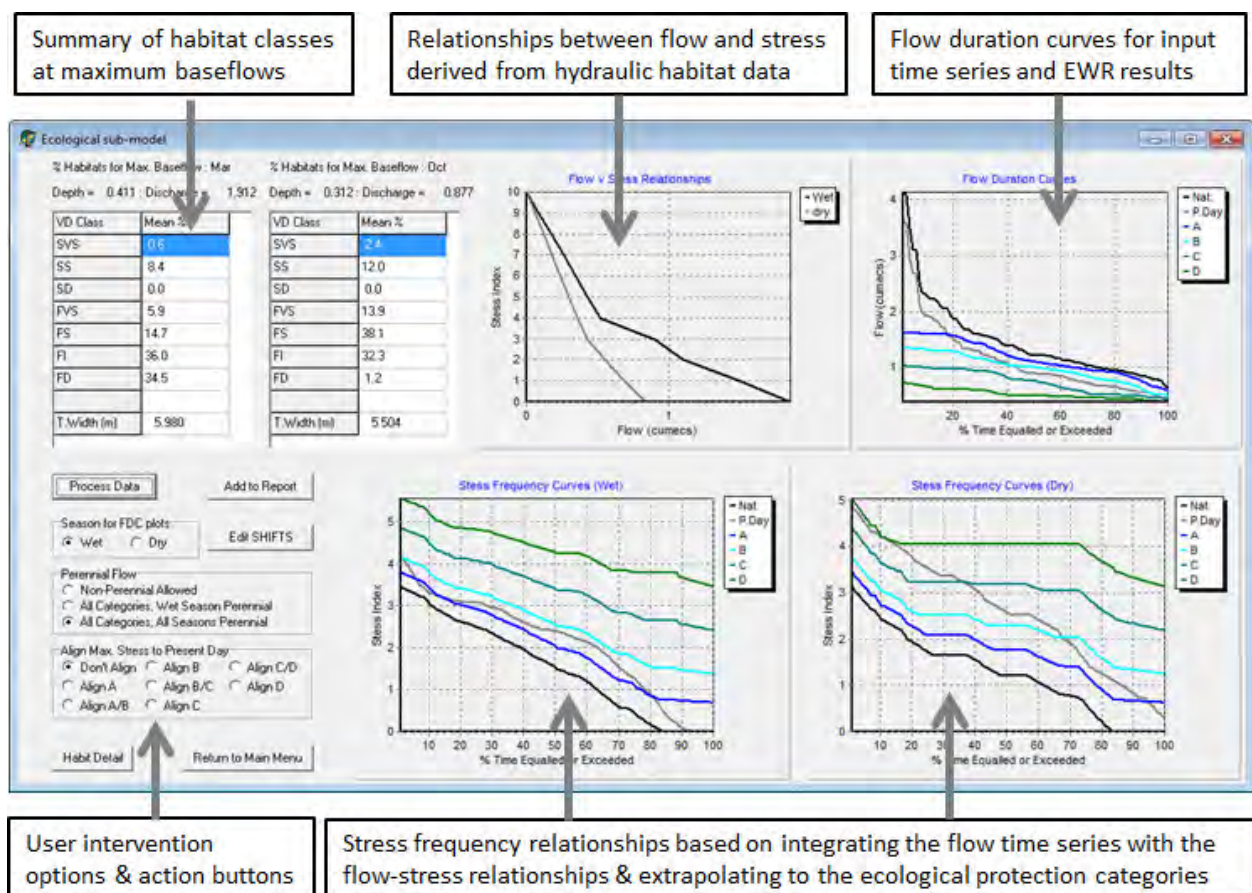


Figure 3-2 Screenshot of the Ecological Sub-Model

The EWR requirement option generates the final results for all EWR categories. The results are summarised as FDC plots, time series plots and mean annual volume as million m<sup>3</sup> (MCM) as well as % of mean annual natural runoff (nMAR) for each month. The main output is therefore the long-term mean annual volume requirement and the FDC or rules (part of the report – see discussion below) for each calendar month.

An option is included in each sub-model to add information generated by the sub-model to the report for later saving or printing. An option on the main screen of the RDRM (Figure 3-1) is available to view the report and to output the report to a text file.

## **4 DESIGN OF THE HYDRAULIC SUB-MODEL**

Literature reviews have been undertaken to establish the background to EF studies, specifically the role of hydraulics in these studies. Reviews of open channel hydraulic theory and hydraulic parameter estimations were also undertaken to obtain an understanding of ecohydraulic inputs, modelling and outputs. These reviews have provided the foundations for the establishing design requirements of the hydraulic sub-model. Details of the design concepts of the hydraulic sub-model, the sub-model parameter requirements, the sub-model structure and the data sources to estimate these parameters are discussed in this chapter.

### **4.1 Design Considerations**

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/characteristics from readily available information for any part of the country. The following three basic principles have been established on the basis of the essential requirements for a desktop ER determination model and the need to incorporate more of the emerging science of EFs:

- The model should be able to translate habitat requirements as defined by the ecological 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 hydrological sub-model to define flow requirements.
- The input data requirements should be based on readily available information that can be accessed from existing data sources (numerical, GIS or map information) relating to topography, geomorphology, geology and possibly vegetation.
- 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 computational code must allow for 'intelligent' user intervention where some, or all, of the default regional input data can be defined by the user. This is in line with the current

version of the DRM and allows the model to be used for different levels of ER determination.

## 4.2 Sub-Model Parameter Requirements

Ecohydraulic results are generally provided as look-up tables (Table 2-6) relating discharge to ecologically relevant hydraulic parameters; maximum and average depth, width, wetted perimeter, average and maximum velocity (using statistical velocity distributions for 1-D models), as well as the relative spatial composition of hydraulic habitat conditions defined using flow classes for fish and invertebrates (Figure 2-5).

The starting point to determine the abovementioned hydraulic parameters and flow classes would be to generate a representative cross-sectional profile. The main characteristics of a river cross-section can be generated from the following parameters:

- *Channel shape* (i.e. rectangular, trapezoidal, parabolic, V-shaped)
- *Maximum channel width at bankfull discharge (m)*
- *Base, or bed width* - In the case of rectangular and trapezoidal channel shapes, quantified as a percentage of the maximum width
- *Maximum channel depth at bankfull discharge (m)*
- *Macro and Micro roughness size (m)* – The distribution of flow-depth classes is dependant upon the roughness variability observed within a cross-section. A ‘smooth’ cross-section will produce predominantly slow-deep classes and a ‘very rough’ section will result in predominantly fast-shallow classes. In order to achieve the variability of the flow class categories observed from measured data, it was necessary to produce a cross-section that featured the roughness elements. This was achieved by perturbing the basic channel shape with two roughness types:
  - *Macro roughness size (m)* – defines 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)* – define the smaller scale roughness elements that make up the cross-section (typically sand, gravel and cobbles)

The next step would be to generate a representative rating curve (Equation 2-6 and Figure 2-7). To develop a rating curve, discharge is required and can be related to resistance. As discussed in Section 2.2.1, the Manning formula (Equation 2-2) is simple and it is the preferred option for use in ER studies. It was therefore decided to use the Manning formula and the generated cross-sectional profile to produce the representative rating curve. This procedure would require the estimation of Manning's  $n$  and gradient as functions of depth.

### **4.3 Hydraulic Sub-Model in the Revised Desktop Reserve Model**

The parameters to generate the cross-section and rating curve were obtained through the development of estimation equations as part of the study and details of their development are provided in Chapters 5 to 7. The hydraulic sub-model programme structure is illustrated in Figure 4-1 and a flow diagram of how the parameters are computed in the hydraulic sub-model is provided in Figure 4-2 along with references to where further details of each relationship can be found.

A screenshot of the hydraulic sub-model interface for the RDRM is illustrated in Figure 4-3. The parameter list on the left hand side of the screen lists the main parameters of the model that will be read in through the *Regional Hydraulic Model Parameter* input requirement or be 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 Geo Zone (integer value between 1 and 6 representing Geomorphological Zones A to F), the Flood Region (integer value between 1 and 13 – see Figure 2-8 and Table 2-9), the valley slope (fraction) and the Catchment Area (km<sup>2</sup>). The other values will be calculated based upon the relationships developed in this thesis (Table 7-4).

Geo Zones are related to specific valley slope ranges (see Table 4-1 and discussion in Section 6.5) and 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 corrected valley slope will be set to the median value of the valley slope range of the specified Geo Zone.

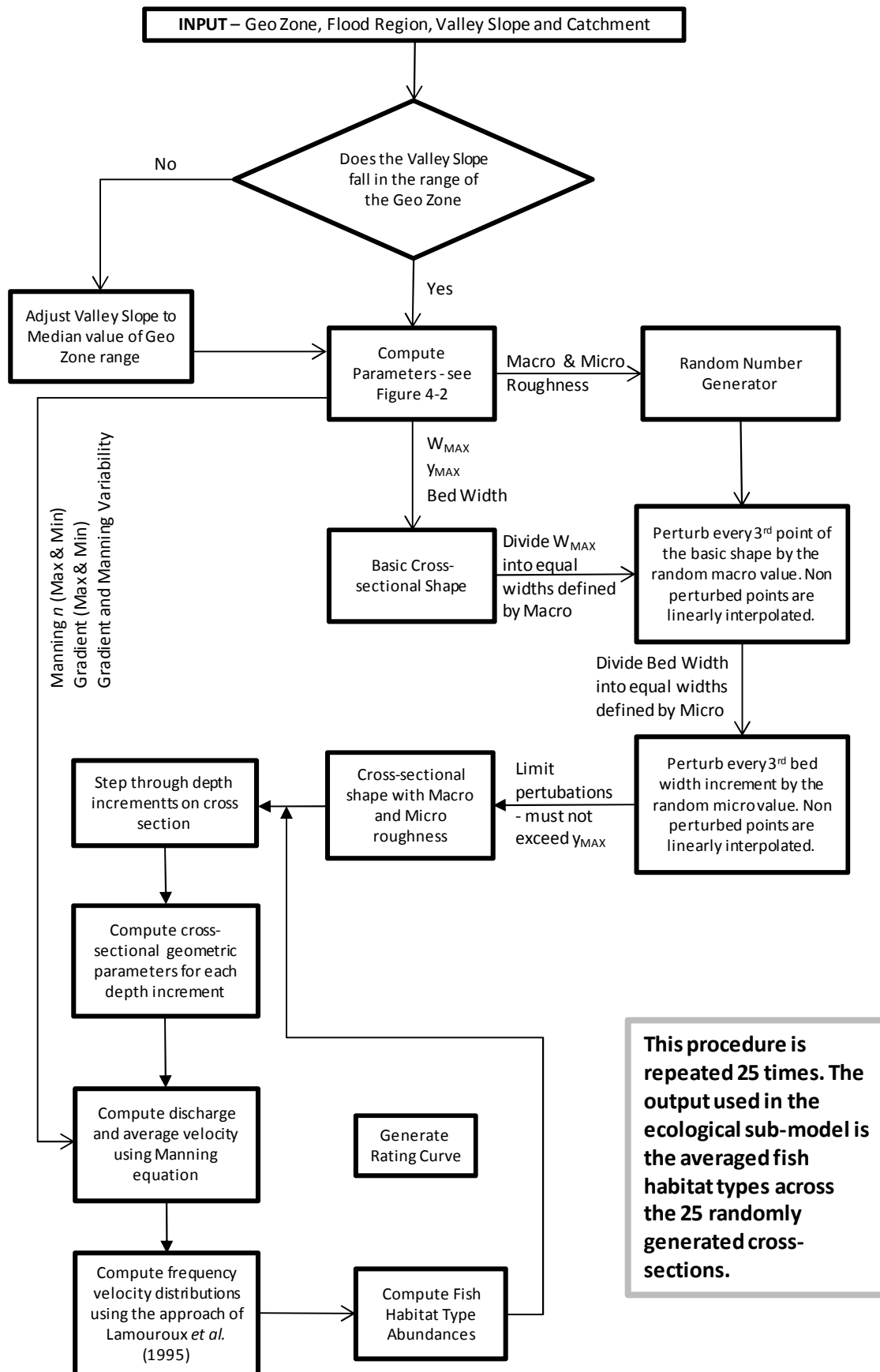
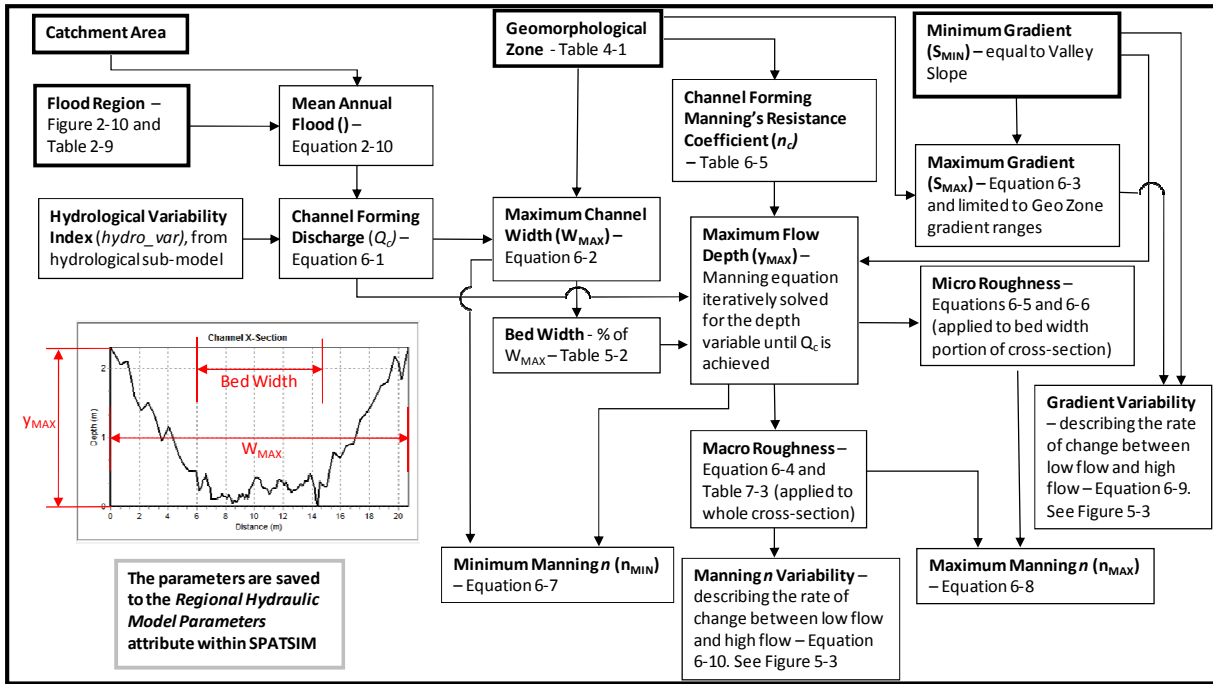
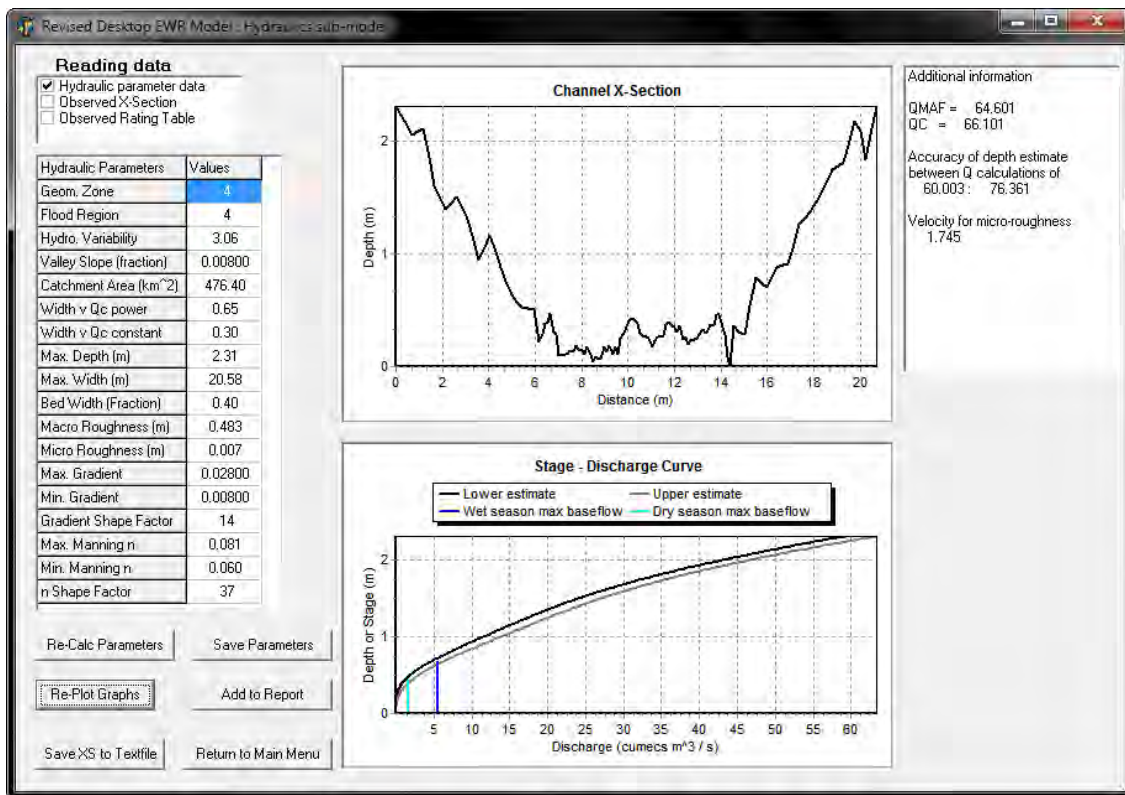


Figure 4-1 Flow Diagram Illustrating the Structure of the Hydraulic Sub-model



**Figure 4-2** Flow Diagram of Hydraulic Sub-model Parameter Computations – the input parameters are illustrated in bold boxes



**Figure 4-3** Screenshot of the Hydraulic Sub-model Interface in the RDRM

The normal user interventions would be to change the values of the Geo Zone, Flood Region, Valley Slope and Catchment Area and then click on 'Re-Calculate' and 'Re-Plot Graphs' to compute the values of the other hydraulic parameters. Selecting "Save Parameters" saves the results back to SPATSIM for future use. The other parameter values may be changed and the effects of the adjusted parameter can be observed in the two graphs by clicking on the 'Re-Plot' button. However, it will not be normal practice for a user to change any of the calculated parameters unless they are fully conversant with the hydraulic sub-model and the analysis methods used.

The hydraulic sub-model applies the equations and methods discussed in Chapters 6 and 7 to generate 25 cross-sections and associated hydraulic data (rating curve and habitat information). This approach has been adopted to account for at least some of the uncertainties associated with using a randomly generated cross-section shape. Previous trials indicated that there is very little difference in the final result in the number of cross-sections generated is greater than approximately 15 and therefore 20 sections has been selected to minimise computer processing time. The two graphs shown on the screen are (i) the final cross-section (out of an uncertainty sample of 25) that has been generated by the model and (ii) 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 obtained from the hydrology sub-model. 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 Hydrological Variability (listed as Hydro. Variability in the sub-model and the value is obtained from the hydrological sub-model – see Section 6.1 for further details). To view this information it is necessary to click on the 'Re-Calc Parameters' button. This display box also provides the user with details of the velocity value used in the micro roughness relationship (Equations 6-5 and 6-6) and the values of the discharges calculated for the last 2 iterations in the maximum flow depth computation (Section 6-4). These two values were used to check the accuracy of the maximum depth computation (i.e. for the computed maximum depth, is the channel forming discharge between these two values).

A facility for replacing the randomly generated channel cross-section or rating curve based on a set of regional parameters and estimation equations with a surveyed channel cross-section or rating curve is located in the top left ('Reading data') but the facility is not active in the current model as additional guidelines will need to be developed to ensure that the observed cross-section is compatible with the other parts of the RDRM.

The outputs from the hydraulic sub-model that are used within the ecological sub-model are the distributions of the 7 habitat types based on different combinations of depth and velocity (see Figure 2-5 fish flow classes and Table 8-1) within the channel cross-section for all possible water depths and averaged across the 25 randomly generated cross-sections. These habitat distributions are determined using the approach of Lamouroux *et al.* (1995) as recommended by Hirschowitz *et al.* (2007).

#### **4.4 Data Sources**

The selection of appropriate variables for the estimation equations was based upon the 2<sup>nd</sup> design principle i.e. 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 of the availability of these data sets were undertaken. The data sets selected for use in the hydraulic sub-model are highlighted in the list below with detailed discussions provided later in this section.

*The types of variables that were expected to affect the channel cross-sectional shape were:*

- **Topographical (generally available from topographic maps or Digital Elevation Models, DEM), including:**
  - **Position in the hydrological landscape (headwater, mid-reach or downstream reach)**
  - **Local longitudinal gradient**
  - **Degree of incision**
  - **Valley cross-sectional 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 - Midgely *et al.*, 1994 or WR2005 - Middleton and Bailey, 2008), 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-resistance relationships are:*

- Substrate type, in turn related to (refer to the above points):
  - Geology
  - Sediment load
  - Channel size and gradient
  - In channel vegetation

*The types of variables that are expected to affect depth-energy gradient relationships are:*

- **Topographic and/or geomorphologic, including:**
  - **Broad channel types (bedrock, alluvial or mixed) and the sequences of pools, runs and riffles that often occur in natural river systems (van Niekerk *et al.*, 1995)**
  - **Existing geomorphological characteristics of rivers (Rowntree and Wadeson, 1999)**

The initial expectations were that the physical variables could include measures of topography, geology, geomorphology, hydrology and vegetation cover. The highlighted items in the above lists are discussed in more detail below:

- **Topographical**

**Topographical maps** – The Chief Directorate: National Geo-spatial Information (CD:NGI) is the national mapping agency of SA. The CD:NGI produces topographic map series (hard copies and electronic versions) at scales of 1:50 000; 1:250 000 and 1:500 000. The maps contain details such as contours and spot heights which could be used to determine the river valley slope.

The 1:50 000 map series is organised into grids with respect to longitude and latitude position line. Each grid reference contains a maximum of 16 maps and the complete set consists of 1915 maps. The contours of the 1:50 000 map series are in 20m intervals.

**Shuttle Radar Topography Mission (SRTM)** - is an international research effort that obtained DEMs on a near-global scale from 56° S to 60° N, to generate the most complete high-resolution digital topographic database of the Earth (Wikipedia, 2011). The elevation models derived from the SRTM data may then be used in Geographic Information Systems (GIS) to quantify some of the desired parameters, e.g. valley slope.

The elevation models are arranged into tiles, each covering one degree of latitude and one degree of longitude, named according to their south western corners. It follows that "n45e006" stretches from 45°N 6°E to 46°N 7°E and "s45w006" from 45°S 6°W to 44°S 5°W. The resolution of the cells of the source data is one arc second, but 1" (approx. 30 metre) data have only been released over the United States territory; for the rest of the world, only three-arc-second (approx. 90m) data are available. SRTM data can be downloaded freely over the Internet, and their file format (.hgt) is supported by several GIS software packages.

- **Hydrological**

**WR90:** These are *Surface Water Resources of South Africa* publications (WR90 – Midgely *et al.*, 1994). The surface water resources of SA and related data were assessed and methods developed primarily for use in surface water resource simulations. The publications consist of an extensive database of naturalised monthly streamflow characteristics, including monthly time series for a period from October 1920 to

September 1990. The study generated information at a quaternary level for the whole of SA, Lesotho and Swaziland (a total of 1946 catchments varying in size from below 100km<sup>2</sup> to above 10 000km<sup>2</sup>, with the larger catchments generally occurring in the drier parts of the country and the smaller in the wetter parts). The information includes dams, evaporation, geology, land cover, rainfall, recorded and simulated runoff, rivers, sediment yield, soil, settlement locations and vegetation types.

**WR2005:** The WR2005 study (Middleton and Bailey, 2008) was commissioned by the WRC in 2004 to include data beyond 1990 and to refine some of the WR90 information. The objective of the study was not to merely update the WR90 data, but to re-evaluate, improve and, if necessary, redevelop the tools to be applied in WR2005 with the knowledge of new developments and analyses.

The applicable databases found in WR90 and WR2005 for this study are: catchment area, recorded and simulated runoff and a river channel GIS coverage. The sediment yield, soils and vegetation databases in the WR90 and WR2005 were found to be broadly grouped and unsuitable for use in this research project as the data sets were either coarse or insufficient for the resolution required for the development of the hydraulic sub-model.

- **Geomorphological**

**Geomorphic Provinces** – Partridge *et al.* (2010) determined 34 geomorphic provinces and 12 sub-provinces within South Africa, Lesotho and Swaziland (Figure 4-4). Significant changes in longitudinal slope and valley cross-sectional width for ninety-nine main stem rivers produced 471 macro-reaches. Each macro-reach was then analysed using a variety descriptions including shape, best fit curve, slope, sediment storage potential and valley width and thereafter grouped into the distinct geomorphic provinces. A similar geomorphological characterisation has been undertaken by Thoms *et al.* (2002) and further related the physical factors to ecosystem structures and processes. Thoms and Sheldon (2002) has adopted this characterisation approach to develop an ecosystem approach to determine EF for Australian dryland river systems.

**Geomorphological Zones (Geo Zones)** – Rowntree and Wadeson (1999) and Rowntree *et al.* (2000) developed a longitudinal river zonal classification system for South African rivers modified from Noble and Hemens (1978). Initially, each zone was given 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 difference can be identified from an analysis of gradients. The zones were therefore classified according to channel gradients measured from 1:50 000 topographic maps. The zones were referred to as geomorphological zones (Geo Zone) and the classifications derived are tabulated in Table 4-1.

Based on the Rowntree *et al.* (2000) classification, the geomorphological zones for the country have been mapped by Moolman (2008). While Rowntree *et al.* (2000) used the river channels and contours from 1:50 000 map sheets, Moolman (2008) used the river channels of the Department of Water Affairs (DWA) 1:500 000 river coverage (adjusted to within 50m of 1:50 000 rivers) and a 20 x 20m resolution DEM.

The geological, sediment/substrate and vegetation data sets reviewed were found to be unsuitable for application in this study. However, the data sets that were found are expected to be adequate to achieve the objectives of the developing a desktop hydraulic sub-model.



**Table 4-1 Geomorphological Zonation of River Channels (after Rowntree and Wadeson, 1999; Rowntree *et al.*, 2000)**

Longitudinal Zone	Macro-Reach Characteristics		Characteristic Channel Features
	Gradient Class	Zone Class	
<b>Zonation associated with a 'normal' profile (i.e. characteristic concave profile)</b>			
<b>Source zone</b>	not specified	S	Low gradient, upland plateau or upland basin able to store water. Spongy or peaty hydromorphic soils.
<b>Mountain headwater stream</b>	> 0.1	A	Very steep gradient streams dominated by vertical flow over bedrock with waterfalls and plunge pools. Normally first or second order. Reach types include bedrock fall and cascades.
<b>Mountain stream</b>	0.04 - 0.99	B	Steep gradient stream 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.
<b>Transitional</b>	0.02 - 0.039	C	Moderately steep stream 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.
<b>Upper Foothills</b>	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.
<b>Lower Foothills</b>	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 typically include pool-riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present.
<b>Lowland river</b>	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.

## 5 ESTIMATION OF HYDRAULIC PARAMETERS USING OBSERVED DATA

The development of the hydraulic sub-model parameters relationships consisted of three phases. The first phase was to use hydraulic data from past EWR studies to generate parameters which would be used to develop the estimation relationships (Phase 2). The third phase consisted of testing the estimation relationships developed and refining these relationships where necessary. This chapter provides a discussion of the past EWR hydraulic data analysis and the development of the relationships are discussed in Chapter 6. Testing and refinement of the relationships is discussed in Chapter 7.

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

- **Runoff** – Natural Mean Annual Runoff (nMAR) ( $10^6 \text{ m}^3 \text{ y}^{-1}$ ) obtained from the WR90, WR2005 reports or from site specific hydrological assessments and scaled to the EWR site location. Scaling was typically done on a catchment area basis, which is unlikely to be very accurate for small catchments within larger areas which have significant spatial variations in either runoff response or rainfall inputs (Hughes, 2004a).
- **Site Location** – Latitude, Longitude, Altitude
- **Geomorphological Zone** – A to F (Table 4-1)
- **Sediment Types and/or Sizes**
- **Hydraulic Data**
  - Discharge,  $Q$  ( $\text{m}^3 \text{ s}^{-1}$ ),
  - Maximum flow depth,  $y$  (m),
  - Average flow depth,  $y_{av}$  (m),
  - Cross-sectional flow area,  $A$  ( $\text{m}^2$ ),
  - Inundated width,  $W$  (m),
  - Wetted perimeter,  $P$  (m),
  - Average velocity,  $V$  ( $\text{m s}^{-1}$ ),
  - Inundated width ( $W$ ) for maximum flow depths ( $y$ ) of 0.10, 0.20 and 0.30 m,

- Water surface gradient,  $S$  ( $\text{m m}^{-1}$ ),
- Valley slope,  $VS$  (topographical map or similar),
- Manning's flow resistance coefficient,  $n$  ( $\text{s.m}^{-1/3}$ ),
- Rating curve coefficients (a, b and c, with a maximum of three curves allowed)

A total of 300 out of the 359 sites from the hydraulic database were selected for use in the analysis. Insufficient cross sectional or rating curve information was the reason for excluding the other 59 cross-sections. The surveyed cross-sectional profile data associated with the selected sites were collated from various hydraulic or EF management consultants that were involved in the past EWR studies.

The development of a software program (henceforth referred to as an estimation program) facilitated the processing of the large amount of data. The objective of the estimation program was to explore different combinations of hydraulic parameters that can be used to generate appropriate parameter values that closely approximate the cross-sectional profile and rating curve characteristics of each site. A screenshot of the estimation program is illustrated in Figure 5-1 and a discussion of the parameter estimation process is provided below.

The estimation program included a facility to import, as simple text files, the observed (i.e. surveyed) cross-sectional profile (elevation vs. chainage) and the rating curve (depth vs. discharge). The cross-sectional text files were generated from the reduced survey data. The rating text files were generated using the rating equation (Equation 2-6) and the coefficients for the rating equation were obtained from the hydraulic database (Birkhead and Desai, in press).

After importing the text files, the first step in the parameter estimation process is to specify the maximum depth. The maximum depth value specified was based upon identifying the level at which bankfull flow occurs. This maximum depth value was thereafter used to define the basic shape. The basic shape can either be parabolic, V-shaped or rectangular with varying bed widths (as a % of total width). The program computes the 'best' basic shape by comparing all possibilities with the observed cross-section and optimising the fit to

the relationship between cross-sectional area and water depth (see Figure 5-1, top right hand side) and draws this in red superimposed onto the observed cross-section (see Profile Graph - Figure 5-1). If an inappropriate maximum depth was specified, the result was a basic shape that was not representative of the observed channel shape and alternate maximum depths were specified until a sensible basic shape is drawn. The maximum width is thereafter computed by determining the distance across the observed cross-section at the maximum depth.

A minor alteration was included, during the initial estimation exercise, which involved allowing for a non-symmetrical shape. This was done in order to allow for greater accuracy in the reproduction of the observed cross-section shape. Effectively this meant that when the initial shape is determined the channel bottom could be offset from the centre of the observed channel. This had very little effect on the way in which the rating curve was estimated, but did have an effect on fitting the parameters defining the channel geometry i.e. width and roughness (macro and micro) elements. Figure 5-2 illustrates the differences obtained in the channel geometry and contains two screenshots. The top screenshot is the estimated result from the initial algorithm ('Initial Result') and the bottom screenshot is the estimated results after the algorithm was adjusted to allow for non-symmetrical shapes ('Re-assessment Result'). The 'Initial Result' produced a parabolic shape, while the 'Re-assessment Result' produced a trapezoidal shape and an improved representation of the observed cross-section.

The second step is to 'Get Macro Roughness' which is the parameter (Macro) that defines the large roughness elements that make up the cross-section (typically large boulders and rock outcrops, or other variations in the cross-section) and the third step is to 'Get Micro Roughness' which is the parameter (Micro) that defines the small roughness elements that make up the cross-section (typically sand, gravel and cobbles). The macro and micro roughness parameters determine the minimum and maximum values of a uniform distribution that is used in a random number generator to define perturbations from the basic channel shape. The basic channel shape is first divided into a number of elements with equal widths defined by Macro. A random number (using a uniform distribution between  $-Macro$  and  $+Macro$ ) is generated for every 3<sup>rd</sup> point and this number used to

perturb the basic shape. The elevation of intervening points (those not initially perturbed) are then determined by linearly interpolating between the points that have been perturbed. After the Macro parameter has been fixed, the same process is applied to either the bed width part of the cross-section for trapezoidal shaped channels or the central 10% of the total width for V-shaped and parabolic basic channel shapes. The final part of the random perturbation process involves adjusting all of the elevations to ensure that the maximum depth remains as previously defined and so that no points are above the channel banks.

Optimum roughness values are determined by optimising the fit to the relationship between cross-sectional area and water depth in the same way as the basic shape is determined. (see Figure 5-1, top right hand side). The optimisation process is based on maximising the coefficient of efficiency (Nash and Sutcliffe, 1970 - equal to 1.0 for perfect fit). The coefficient of efficiency is a widely used statistic in hydrology for comparing observed and simulated sequences of values. The optimisation process is achieved through repeated runs using different roughness values (macro roughness is optimised first, followed by micro roughness). Repetition of steps 2 and 3 can reveal the extent of the uncertainty in the determination of these roughness values, as a different random sample of channel elements is generated each time. If the values of the roughness parameters vary substantially with each repetition, there is clearly a lot of uncertainty about the best values to use. To help control the macro roughness optimisation, an option was available to specify a minimum macro roughness. By specifying a minimum macro roughness, the optimisation process would not consider the lower values and the uncertainty would be reduced.

The next part of the estimation process is to estimate the parameters required for generating a rating curve. These parameters were identified (Section 4.1) as the Manning resistance coefficient and energy gradient. Hicks and Mason (1998) illustrated plots of Manning's  $n$  vs. discharge for each site and an examination of these plots displayed variations of Manning's  $n$  with discharge. The decrease of Manning's  $n$  with increasing discharge was generally observed in the plots. It is widely accepted that for the main channel portion of a river cross-section, Manning's  $n$  declines with increasing flow depth. The reason for the decline is due to the local physical characteristics contributing to resistance becoming inundated and drowned out as flow depth increases. The energy

gradient is represented by the water surface gradient. In a pool-riffle sequence, the water surface gradient is found to increase in a pool section and decrease in a riffle or rapid section with increase in flow depth (Emmett *et al.* 1983).

The variations of Manning's  $n$  and the energy gradient with flow depth are required when generating the hydraulic sub-model rating curve. Practitioners generally resort to obtaining additional field data to improve hydraulic modelling results but the details of how to quantify these variations is limited. Many natural processes have been found to follow an S-shaped progression and are represented by the use of S-curve functions. The curves show the growth or reduction of a variable in terms of another variable and provide a smooth transition between the upper and lower limits. In SA, Birkhead *et al.* (2000) developed an S-curve type function to compute intermediate energy slopes between the measured low and high flow values for different representative channel types along the Sabie River. Dollar and Rowntree (2003) required energy gradient values in order to extrapolate the measured rating curves for cross-sections along the Mkomazi, Mhlatuze and Olifants rivers and developed an S-curve function as well. Hypothetical S-curve type relationships, as illustrated in Figure 5-3, are therefore used to estimate the variations of Manning's  $n$  and energy gradient with increasing flow depth. The relationships result in values between 1 and 50, where 1 would represent a slow change in the variable with increase in flow depth and 50 would represent a rapid change in the variable with an increase in flow depth, Figure 5-3 illustrates the variability values of 1, 3, 5, 10, 25 and 50.

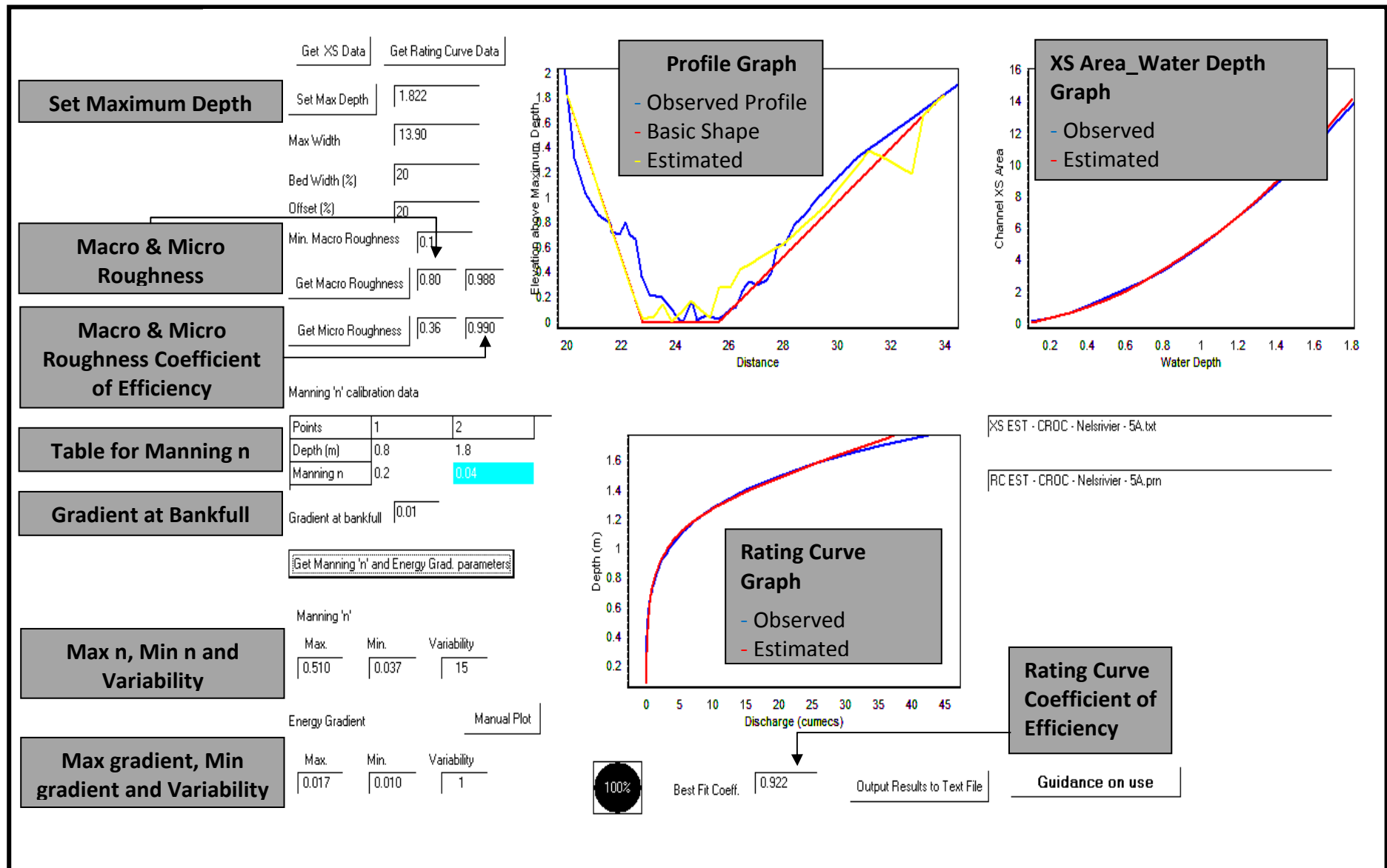
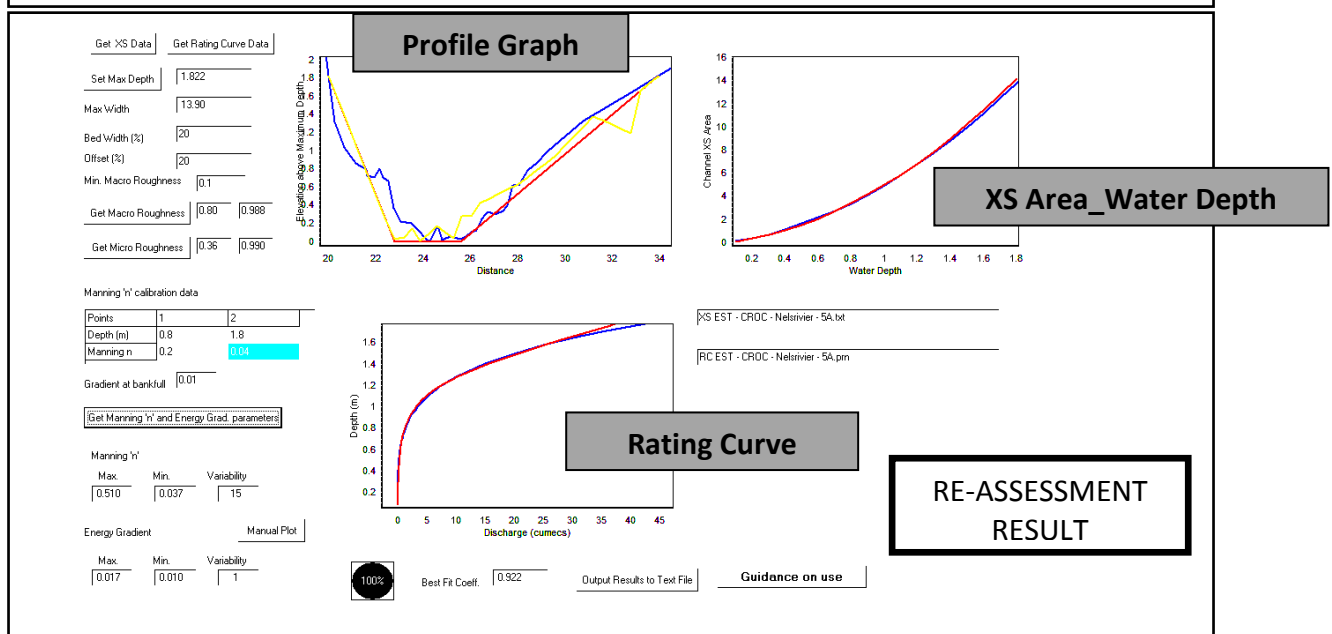
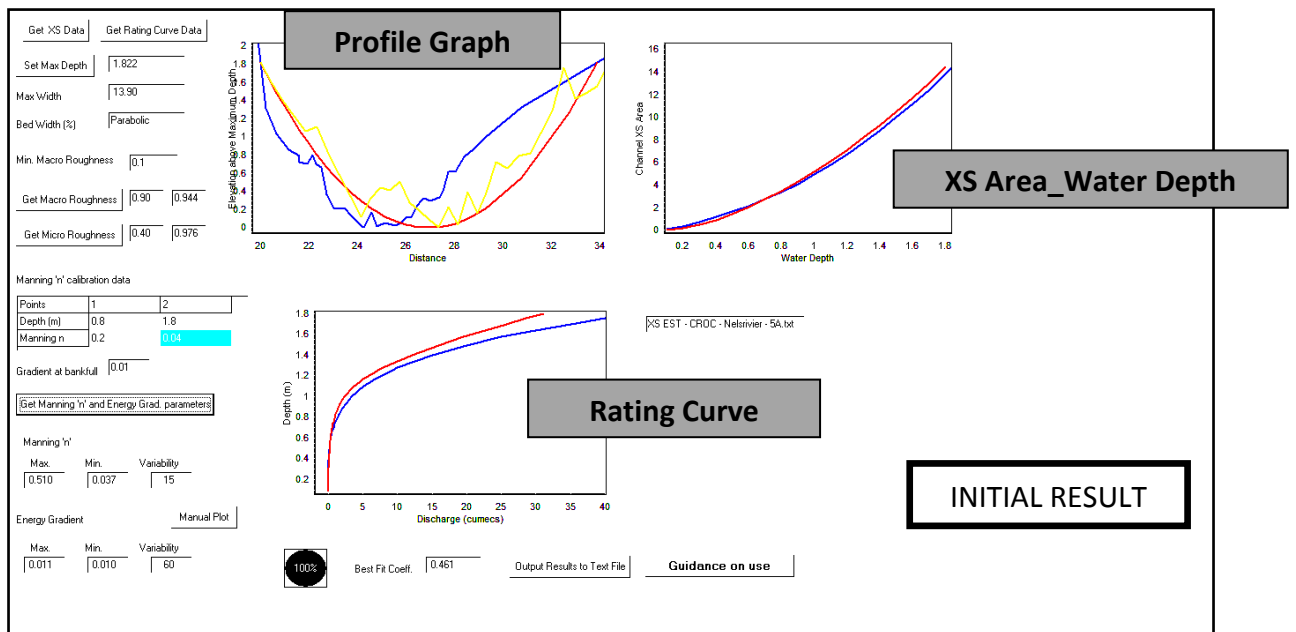


Figure 5-1 Estimation Program for the Hydraulic Parameters (screenshot with explanatory labels). XS = Cross-sectional



**Profile Graph**

- Observed Profile
- Basic Shape
- Estimated

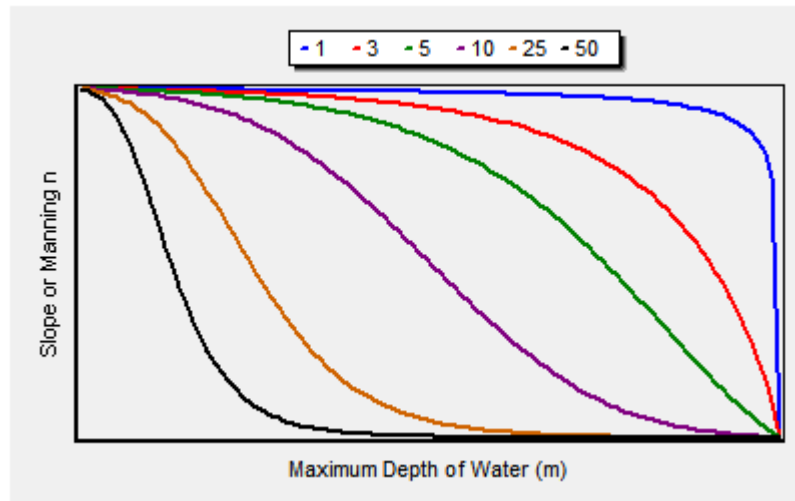
**XS Area\_ Water Depth Graph**

- Observed
- Estimated

**Rating Curve Graph**

- Observed
- Estimated

**Figure 5-2** Screenshot of the estimation program for Crocodile River site 4A indicating the difference in estimated cross-sectional profile – Top = initial result (Parabolic), Bottom = Re-assessment result (Trapezoid). XS = Cross-sectional



**Figure 5-3 Relationships between Water Depth and Gradient or Manning  $n$  for Variability Parameter Values of 1, 3, 5, 10, 25 and 50**

Estimating the rating curve was a relatively complex process requiring additional user intervention, mainly because establishing an appropriate parameter set is difficult without first establishing some boundary values for the rating curve estimation. Figure 5-1 shows the table for Manning’s  $n$  data that allows the user to specify two Manning’s  $n$  values for two water depths and the energy gradient at bankfull discharge. 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. However, in the absence of suitable field data, the ecohydraulic results (i.e. resistance computational files - Table 2-7) were used to establish appropriate boundary values. Ideally, the two depth values should cover the full possible range of depths so that limits of Manning’s  $n$  for the full rating curve can be defined.

Below the Manning’s  $n$  data table is a button (‘Get Manning ‘ $n$ ’ and Energy Grad. Parameters’) that starts the optimisation process for quantifying the parameters of the relationships for Manning’s  $n$  and energy gradient variations with water depth. Using the values inserted in the table, the Manning’s  $n$  and gradient variations between the two data points are computed. Using the variation values, minimum (equating to maximum flow depth as set in step 1 above) and maximum (equating to zero flow depth) Manning’s  $n$  and gradient values are extrapolated. The optimisation process attempts to find the best values of the minimum and maximum Manning’s  $n$  and energy gradient values as well as the variability parameters that will generate a rating curve close to the observed rating curve (Figure 5-1) within the specified data constraints for Manning’s  $n$  and gradient. As with the

process of estimating suitable roughness parameters, the coefficient of efficiency (Nash and Sutcliffe, 1970) is used as the objective function. The bankfull discharge gradient is used as a limit when computing the minimum energy gradient.

There is an option included in the estimation program to allow for the manual adjustment of the estimated rating curve parameters (Manning's  $n$  and gradient – minimum, maximum and variation values – a total of 6 parameters) in order to achieve a better fit. This is included because of the many possible combinations of the 6 parameters and the realisation that sometimes the optimisation process is not able to identify appropriate values (i.e. it will produce good fits to parts of the rating curve at the expense of other parts). Once the user is satisfied with the hydraulic parameters using the estimation program, they can be saved to a text file by selecting 'Output Results to Text File'. The parameters saved to the text file are; Site Name, Maximum Depth, Maximum Width, Bed Width (% of Max. Width), Macro Roughness, Micro Roughness, Manning's  $n$  (Minimum and Maximum), Gradient (Maximum and Minimum), Variability Index (Manning and Gradient) and the two Coefficient of Efficiency values.

These estimated hydraulic parameters were thereafter used in the development of hydraulic estimation relationships and the discussions of their developments are provided in Chapter 6.

## 6 DEVELOPMENT OF HYDRAULIC ESTIMATION RELATIONSHIPS

The random sample of screenshots of the estimation program provided in Appendix A (Figures A-1 to A-4) indicates that the estimation program can be considered appropriate to guide the estimation process. The program structure reproduced the channel geometry and rating curve characteristics of the observed sites reasonably well with 85% of the sites resulting in coefficient of efficiency values greater than 0.75. Weak coefficients of efficiency were obtained in pool situations (i.e. a flow depth was present at the zero discharge condition). However, the next step in the development of the hydraulic sub-model revealed certain inherent flaws and limitations in the estimation program (discussed further in Sections 6.1.1, 6.2.1 and 6.6.1) related to interactions between the parameter values.

The next step in the development of the hydraulic sub-model was to develop hydraulic relationships for the sub-model. This was achieved through the combination of regression and rule-based approaches. Firstly, the regression approach developed standard multiple regression hydraulic relationships using the estimated parameters and guided by equation forms (i.e. power and linear functions) from past literature and secondly, the rule-based approach developed hydraulic relationships based on physical characteristics, technical theory and various assumptions using past experience and literature and partly guided by the regression results.

Rule-based models consist of if-then-else rules that attempt to capture knowledge of experts to develop simplified equations for complex systems. A detailed description of the rule-based modelling technique is provided by Nicolson (1999). Rule-based techniques assist in building up an understanding of how systems respond to changes and the rules developed help clarify the logic used. Rule based modelling approaches have been applied to several riverine disciplines in SA (specifically for the Sabie River) and to riparian vegetation (Jewitt *et al.*, 1998; Mackenzie *et al.*, 1999); fish (Jewitt *et al.*, 1998) and geomorphology (Jewitt *et al.*, 1998) analyses.

The rule-based modelling approach was applied in this study because the regression approach revealed that developing hydraulic relationships contains various uncertainties relating to the complex interaction between the estimated hydraulic parameters. The result

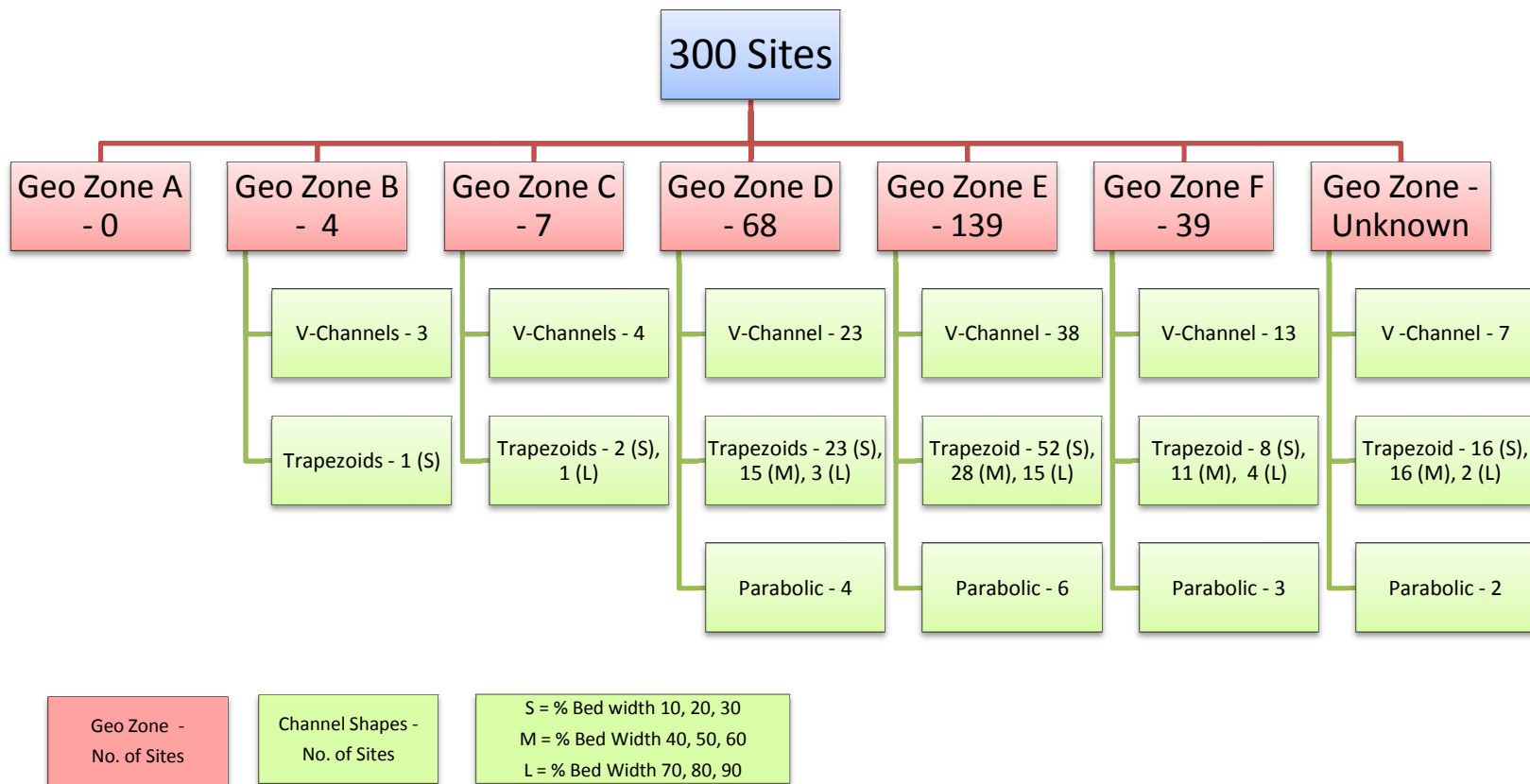
is that the right answer (a realistic rating curve shape, for example) can be obtained for the wrong reasons. That is equivalent to the concept of equifinality (Beven, 2006) where complex hydrological models can produce the same results with different sets of parameters. The uncertainties were further compounded due to 'operator error' in the estimation procedure (discussed later in sections 6.1.1, 6.2.1 and 6.6.1).

The development of the hydraulic sub-model relationships through regression and rule-based approaches are discussed in this chapter. The order of the relationships discussed below is largely governed by the fact that some of the later relationships use the estimates of the parameters discussed first.

The 300 sites from the hydraulic database were categorised into the geomorphic provinces and sub-provinces developed by Partridge *et al.* (2010). The sites were located within 20 of the 46 provinces, with some provinces only containing two data points. It was decided that the geomorphic provinces could not be used to categorise the hydraulic data because no relationships could be developed for the major portion of geomorphic provinces.

The geomorphological zones were thereafter used to categorise the sites into Geo Zones (A – F) and further portioned into channel shape types (Triangular, Parabolic and Trapezoidal). The Trapezoidal channel was categorised into three groups (S,M,L) based on the bed width as a % of maximum width where, S = 10% – 30%, M = 40% - 60% and L = 70% - 90%. The number of sites per Geo Zone and per channel shape is illustrated in Figure 6-1.

The general process in research is that the testing and refinement of relationships are undertaken with a different data set from that which was used during their development. However, the entire past EWR hydraulic data set was needed to estimate the hydraulic parameters because the data was limited in terms of the categories into which they could be placed (Figure 6-1) and consisted of a wide range of hydraulic conditions with no single criteria being appropriate to set aside some data for testing.



**Figure 6-1 Breakdown of Number of Estimated Cross-sections per Geo Zone and Channel Shapes**

## 6.1 Maximum Channel Width

### 6.1.1 Regression Relationships

Power relationships between maximum channel width ( $W_{MAX}$ ) and natural mean annual runoff (nMAR), mean annual flood ( $\bar{Q}$ ) and catchment area (CA) were investigated, and the results are illustrated in Figures 6-2 to 6-4 respectively. The nMAR was obtained from the hydraulic database,  $\bar{Q}$  was determined using Mkhundi and Kachroo (1997) relationships for SA (Section 2.6.2) and CA was digitised, using GIS software for each EWR using the site location from the hydraulic database (Latitude & Longitude), 1 : 50 000 topographical maps and Quaternary boundaries.

The regression relationships have been fitted to all of the data points (including unknown Geo Zones), but additional series have been added to the graphs to try and identify if there are any obvious differences in the relationships for different Geo Zones (B to F). The results suggest no systematic differences between Geo Zones. Substantial scatter is observed in all three series, with power relations producing moderate correlations. The power relations and coefficients of determination ( $R^2$ ) values are tabulated in Table 6-1.

**Table 6-1 Maximum Channel Width Relationships**

Series	Relationship	$R^2$
$W_{MAX}$ vs. nMAR	$W_{MAX} = 9.92(nMAR)^{0.30}$	0.44
$W_{MAX}$ vs. $\bar{Q}$	$W_{MAX} = 5.91\bar{Q}^{0.40}$	0.42
$W_{MAX}$ vs. CA	$W_{MAX} = 5.78(CA)^{0.28}$	0.49

The relationship between maximum width and mean annual discharge is similar to Leopold & Maddock (1953) downstream hydraulic geometry relationships, with their exponent documented as 0.5. It is noted that previous studies in SA by Beck and Basson (2003) concluded that the mean annual flood is an inappropriate parameter to relate to bankfull conditions. However, the MAF was attempted in this study to see if the Geo Zone categorisation could have any influence.

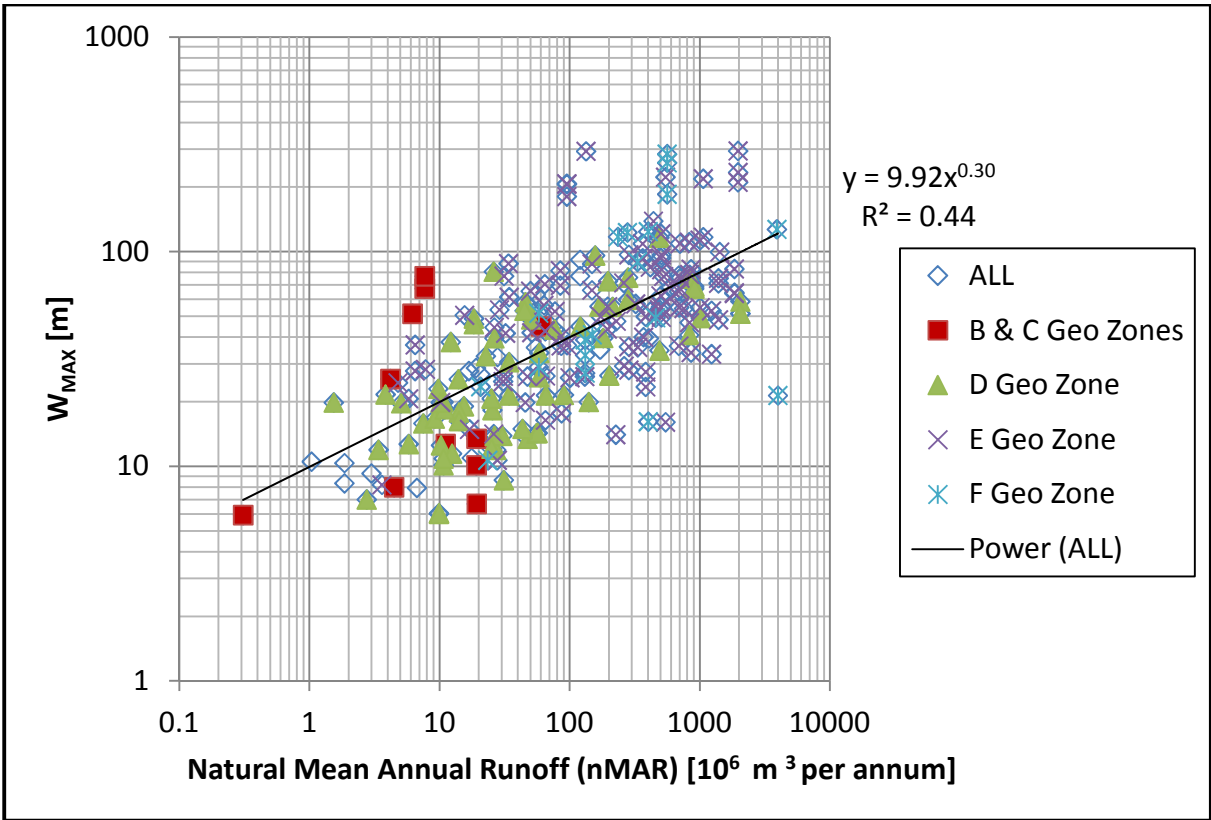


Figure 6-2 Relationship between Maximum Width ( $W_{MAX}$ ) and Natural Mean Annual Runoff (nMAR). ALL = the entire data set

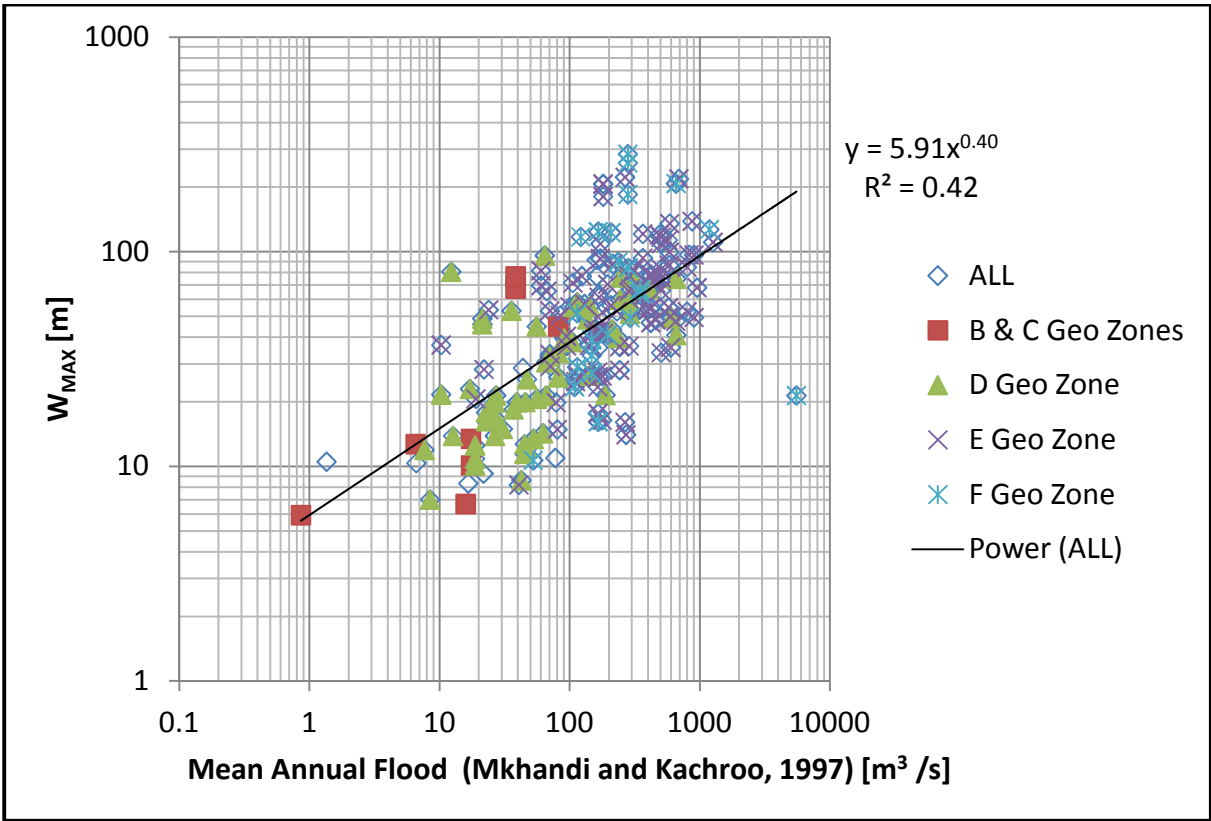
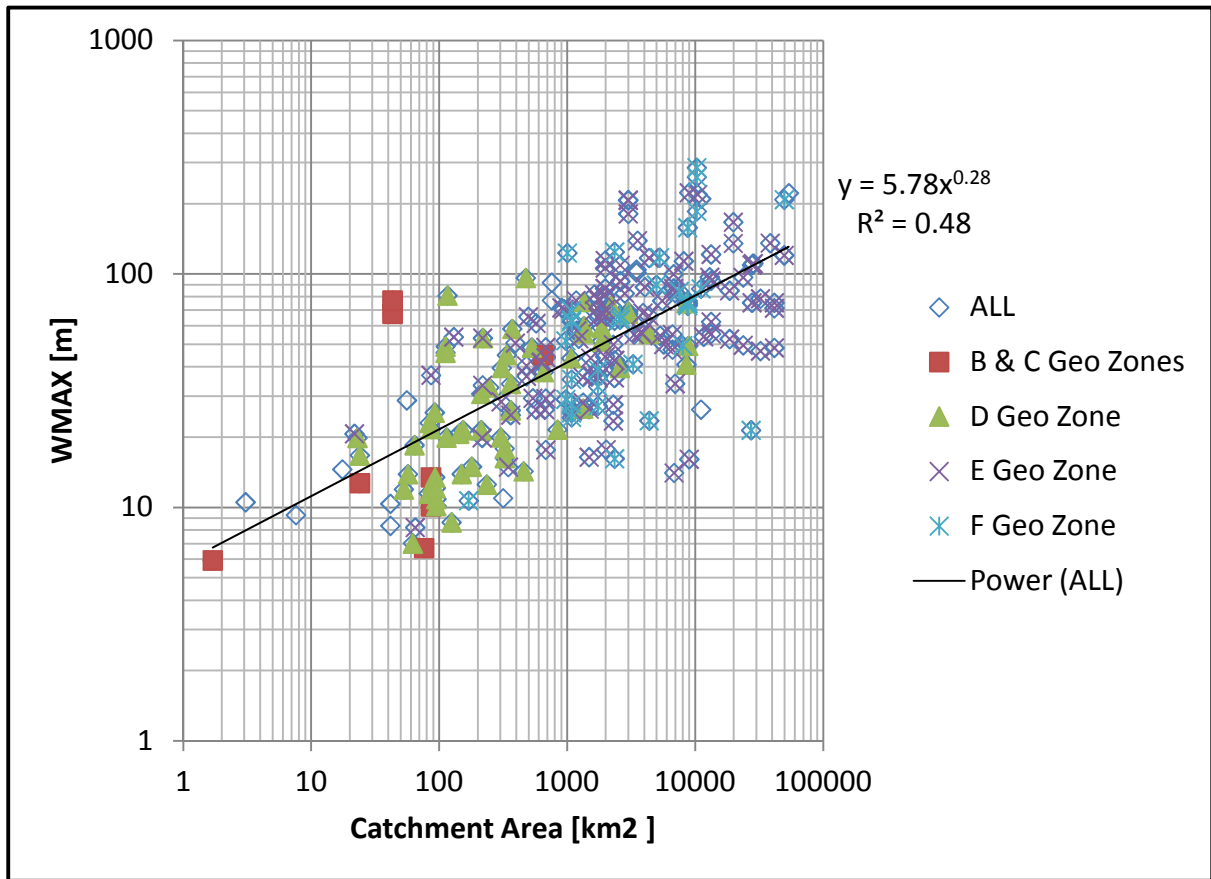


Figure 6-3 Relationship between Maximum Width ( $W_{MAX}$ ) and Mean Annual Flood ( $\bar{Q}$ ). ALL = the entire data set



**Figure 6-4 Relationship between Maximum Width ( $W_{MAX}$ ) and Catchment Area (CA). ALL = the entire data set**

The scatter observed in these series (Table 6-1 and Figures 6-2 to 6-4) may be attributed to the complex interaction of the hydraulic parameters and/or a source of ‘operator’ error. During the estimation process, 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 discharge and to achieve a sensible channel shape. However, in some cases the observed cross-section may not have been fully surveyed as the ER study may have only concentrated on the low flow channel, thus providing insufficient information to identify a bankfull discharge flow depth. The identification of bankfull depth, from a geomorphological perspective, is not a simple matter; particularly when terraces are present that might be unrelated to present day flow regimes (Gordon *et al.*, 2004, Harman *et al.*, 2008).

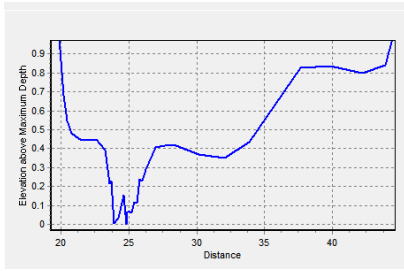
The algorithm to determine the shape of the channel was based upon using the observed cross-section survey points and the maximum depth specified in the estimation program. However, if the survey points did not coincide with the maximum depth specified, the next

closest point would be used. This sometimes resulted in a different shape being computed that is not representative of the observed cross-section and an alternative maximum depth was required to achieve a representative shape. This would result in the use of a maximum channel width that did not represent bankfull conditions. A rather extreme example of maximum depth selections producing alternative widths and channel shapes is provided in Figure 6-5.

### **6.1.2 Rule-based Relationships**

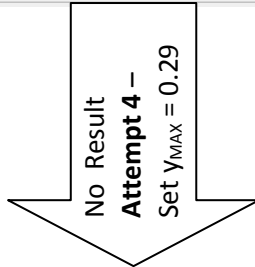
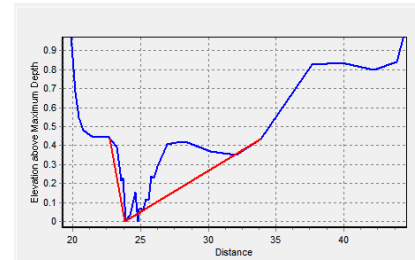
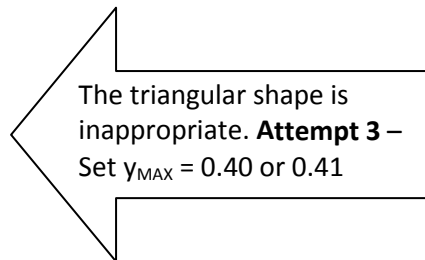
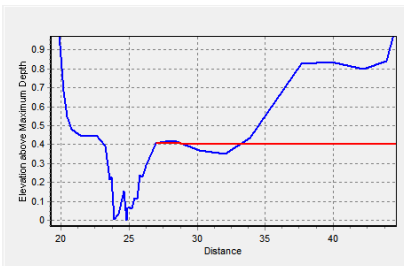
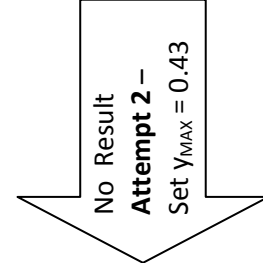
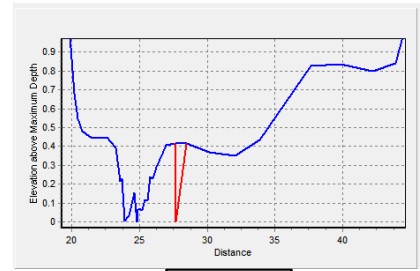
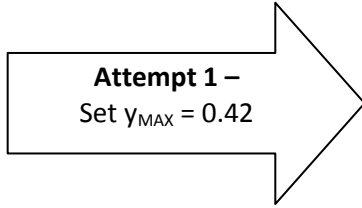
The three regression relationships for  $W_{MAX}$  were moderately correlated and they produced similar trends that have been observed by researchers in the development of relationships to describe hydraulic geometry. However, the estimation of the maximum width was inconsistent in that the values obtained from the estimation program were either for bankfull discharge (as was intended) or for a discharge not representing bankfull conditions because the bankfull depth could not be set using the surveyed cross-section data. It was therefore decided to develop an alternative  $W_{MAX}$  relationship that is consistent with the hydraulic geometry literature, using a power relationship between  $W_{MAX}$  and some measure of channel forming discharge.

Jonker and Shand (2010) noted that various studies have found that the frequency of occurrence of bankfull discharge is relatively consistent with recurrence intervals of between 1 and 4 years, for perennial rivers in South Africa. However, a dominant discharge related to channel form in drier climates could not be represented by discharges with similar frequencies of occurrence. For ephemeral rivers, characterised by infrequent high flood peaks, Jonker and Shand (2010) suggested that channel form be related to higher, less frequent events (such as the 1 in 10 year flood). This implies that hydrology and climate are important considerations for determining the effectiveness of floods to maintain channel form.

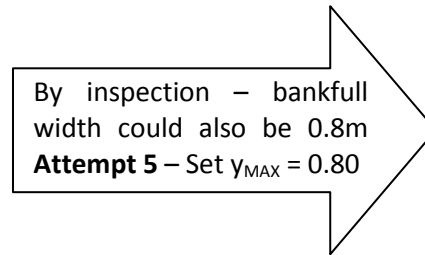
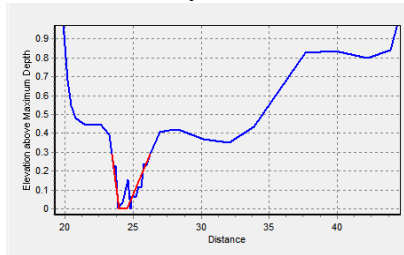


**BEGIN - Import observed cross-sectional profile**

By inspection –  
BANKFULL DEPTH = 0.42m  
and WIDTH = 4m



**Possible Solution**  
Width = 11m, Shape is Triangular –  
Similar results are achieved with varying widths for  $y_{MAX} = 0.3$  to  $0.39$



**Possible Solution**  
Width = 2.86m, Shape is Trapezoid with 20% Bed Width

**Possible Solution**  
Width = 22m, Shape is Triangular - will require a very high macro to achieve a fit (See Figure 6-14 for further details)

**SUMMARY**  
3 possible  $y_{MAX}$  values (i.e. 0.29, 0.43 or 0.80) with 2 basic shapes (Triangular or Trapezoidal)  
  
Bankfull depth could also not feature in the observed cross-section if it was not surveyed

**Profile Graph**  
- Observed Profile  
- Basic Shape

Figure 6-5 Selection of several Maximum Depth ( $y_{MAX}$ ) values and the Resulting Maximum Width ( $W_{MAX}$ ) and Shape

As discussed in Section 2.6.2, 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 flow event ( $Q_{10}$ ) being approximately 1.8 times the mean annual flood ( $\bar{Q}$ ) across all the regions in SA.

In order to be consistent for all cross-sections, 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 the mean annual flood and the 10 year flow event. This variation will depend on the aridity and hydrological variability of the region, with more hydrologically variable regions having a channel forming discharge close to a 10 year flow event and less variable regions will have a channel forming discharge close to the mean annual flood (as reported by Jonker & Shand, 2010).

A hyperbolic tangent function representing an S-curve shape was used to calculate the ratio of  $Q_c / \bar{Q}$ :

$$Q_c / \bar{Q} = \left\{ \tanh \left[ 4 \times \left( \frac{\text{hydro\_var}}{50.0} - 0.5 \right) \right] + 1.0 \right\} \times 0.4 + 1.0 \quad 6-1$$

The use of an S-curve function is a pragmatic approach to introduce assumed non-linearity in the relationship and Equation 6-1 results in a range of values between 1.0 (low variability) and 1.8 (high variability) 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 DRM (Section 2.1.1, Hughes & Hannart, 2003) and is based on the ratio of monthly coefficients of variation and a baseflow index (calculated from the natural hydrology time series).

$W_{MAX}$  is then calculated from the power equation:

$$W_{MAX} = C_w Q_c^{P_w} \quad 6-2$$

where the coefficients  $C_w$  and  $P_w$  were estimated against the observed cross-section profiles. The estimation of the coefficients was achieved through a testing program that

allowed the adjustment of coefficients  $C_w$  and  $P_w$ . A discussion of the testing program and the estimation of the coefficients are provided in Chapter 7.

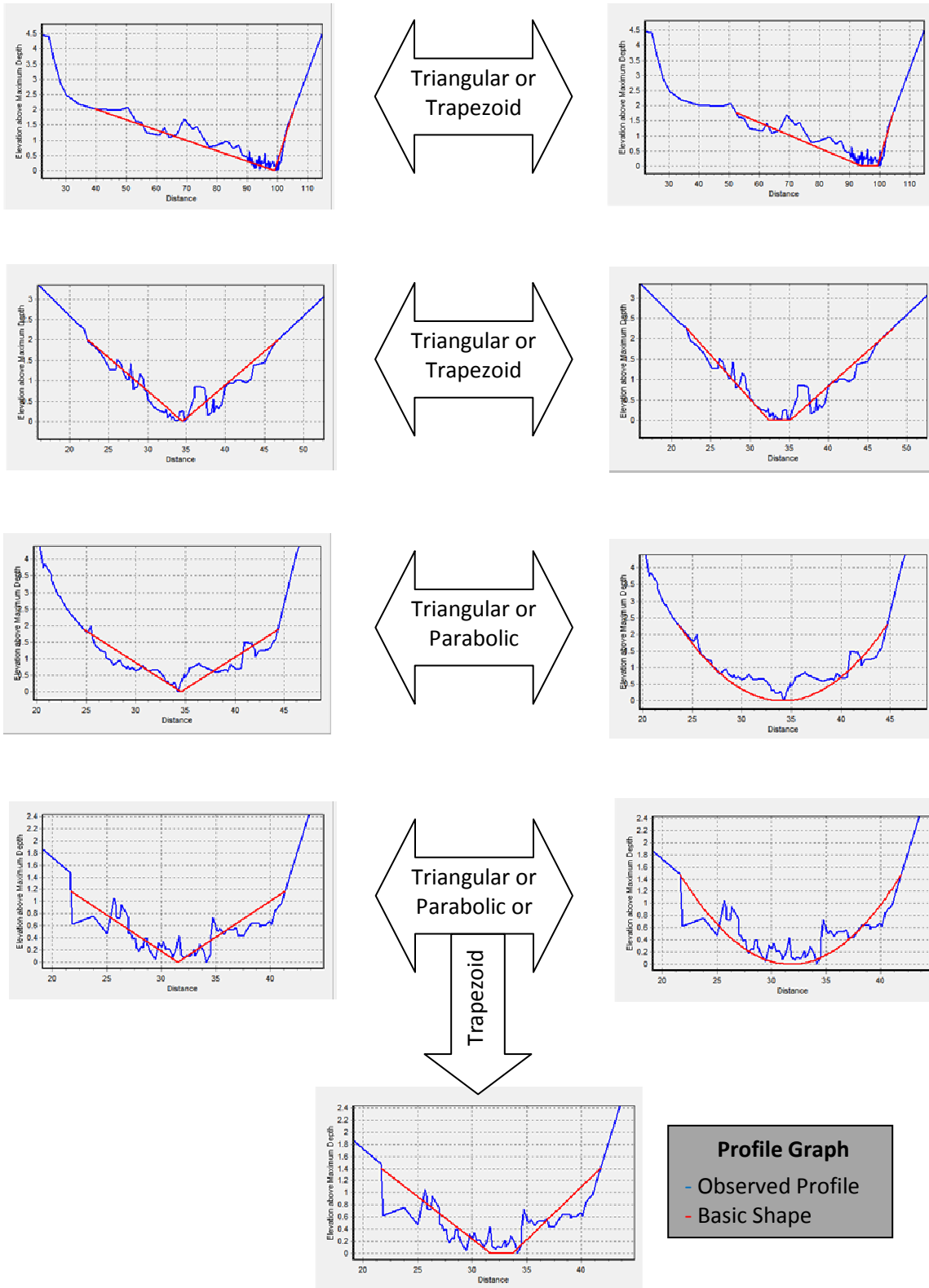
## **6.2 Cross-sectional Shape**

### **6.2.1 Regression Relationships**

The three basic cross-sectional shapes computed in the estimation program were triangular, trapezoidal (with different bed widths) and parabolic. It was initially assumed that the shape of the channel would be related to the Geo Zone, however no systematic differences between Geo Zone and shape could be found (Figure 6-1). Regression relationships between the cross-sectional shape and several physical variables (e.g. valley slope) and/or other parameters (e.g.  $W_{MAX}$ ) were investigated but only poor and generally non-significant correlations ( $R^2$ : 0.15 – 0.25) were achieved. The poor correlations have been attributed to the use of three shape options in the estimation program. It was found that very little difference could be identified between triangular, parabolic and S-type (10 - 30% bed width) trapezoids (Figure 6-1). Figure 6-6 illustrates the effects on shape when the maximum depth is slightly adjusted. 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 channel shapes.

### **6.2.2 Rule-based Relationships**

Monadjemi (1994) indicated that the most widely designed hydraulic section is a trapezoid and it was observed that the channel shapes in published topographical surveys of natural rivers is predominantly trapezoidal. Therefore, the trapezoid shape was selected to represent the basic channel shape for all cross-sections and it was assumed that the bed width would vary from 10% (almost triangular) to 90% (almost rectangular) depending on the Geo Zone (Table 6-2).



**Figure 6-6 Channel Shapes computed from Estimation Program based on changes in Maximum Flow Depth**

Anomalies were observed when categorising the bed width percentages into Geo Zones and it was concluded that the anomalies were a result of how sites are selected. As discussed in Section 2.5, ER sites are selected such that they will produce the most critical and ecologically sensitive habitats. These habitats have been found to occur in rapid and riffle morphological units. However, finding an ER site and therefore a cross-section that is representative of the reach is difficult at times, and a site is selected that may be ecologically sensitive but not representative of the reach. These sites are also different in terms of the cross-sectional geometry because riffles or rapids have steeper local gradients and higher surface resistances than the rest of the reach. The sections where such anomalies were identified were excluded from the categorisation of bed width percentages into Geo Zones because it was unclear whether other factors could have also affected the shape of the channel (e.g. bedrock controlled features may be present).

The final selection of bed width parameter values for different Geo Zones was primarily based on observations from the literature review (Section 2.6.3); headwater channels tend towards triangular (narrow bed width), while lowland rivers tend towards rectangular (wide bed widths). The estimation results were then used to guide the quantification of the parameters given in Table 6-2.

**Table 6-2 Bed Widths Defining Channel Shape According to Geo Zone**

<b>Geo Zone</b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>	<b>F</b>
<b>% Bed Width</b>	10	10	10	30	50	80

## **6.3 Minimum Gradient**

### **6.3.1 Regression Relationships**

The gradient variable in the Manning equation (Equation 2-2) 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. A valley slope is the change in topographical elevation between two points in the river over the length of the river and is measured using a topographic map, or similar source of elevation data, that contains contour lines. A point upstream and a point

downstream of the ER 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.

The high flow water gradient was termed minimum gradient ( $S_{MIN}$ ) in the estimation process. A strong correlation ( $R^2 = 0.95$ ) between minimum gradient and valley slope was achieved (Figure 6-7) 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 quantified using the intersection between a river channel coverage and a DEM with appropriate spatial resolution in a GIS environment as undertaken by Bjerklie *et al.* (2005), Moolman (2008) and Clarke *et al.* (2008) ; once the site has been identified on the river coverage, two intersection points will be located (1 upstream of the site and 1 downstream of the site). The elevations, obtained from the DEM, of the two points and the length of the river between the two points will be recorded. The valley slope will thereafter be calculated by dividing the difference in elevation by the length of the river.

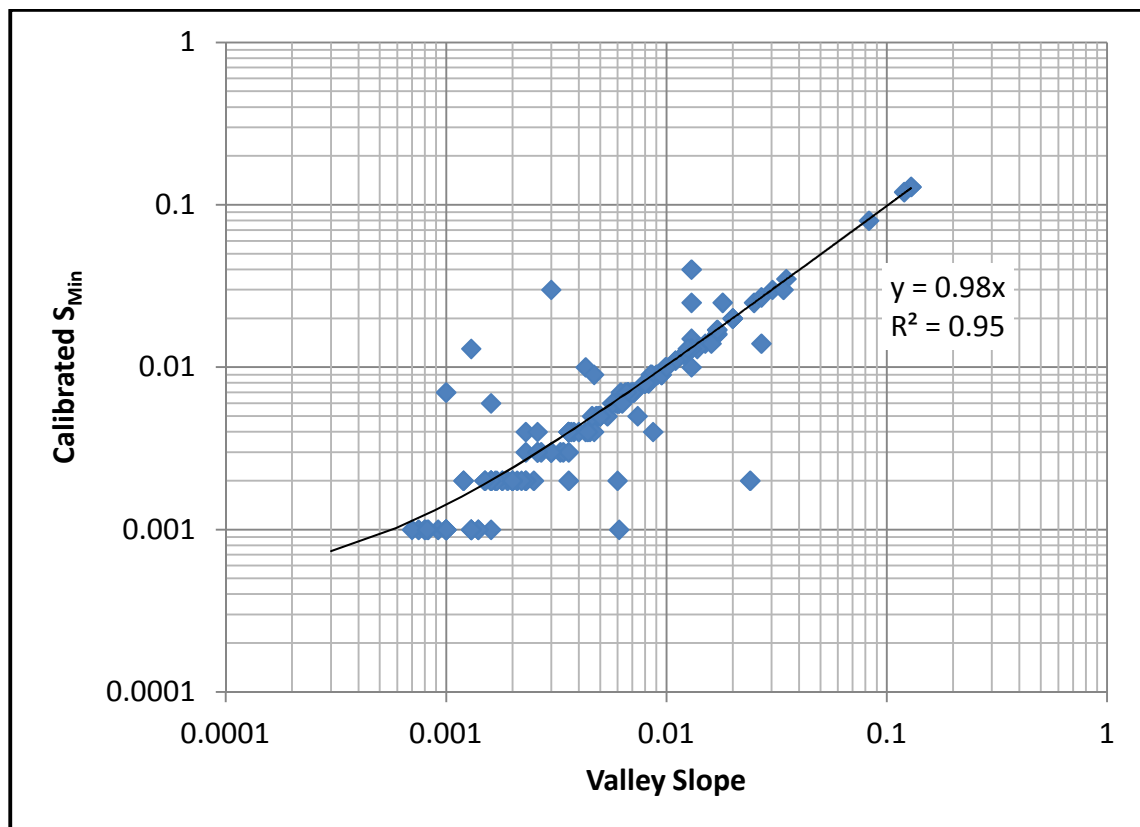


Figure 6-7 Relationship between Estimated Minimum Gradient and Valley Slope

## 6.4 Maximum Flow Depth

### 6.4.1 Regression Relationships

Figure 6-8 illustrates the relationships between maximum depth ( $y_{MAX}$ ) and maximum width ( $W_{MAX}$ ) and Figure 6-9 illustrates the relationship between the ratio of maximum width to maximum depth ( $W_{MAX}/y_{MAX}$ ) and catchment area (CA). 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 Geo Zones (B to F). The results suggest no systematic differences between Geo Zones. Substantial scatter is observed in both series, with power relations producing moderate correlations. The power relations and  $R^2$  values are tabulated in Table 6-3. 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 6-3 Maximum Flow Depth Relationships**

Series	Relationship	$R^2$
$y_{MAX}$ vs. $W_{MAX}$	$y_{MAX} = 0.54(W_{MAX})^{0.37}$	0.41
$W_{MAX} / y_{MAX}$ vs. CA	$W_{MAX} / y_{MAX} = 4.86(CA)^{0.19}$	0.35

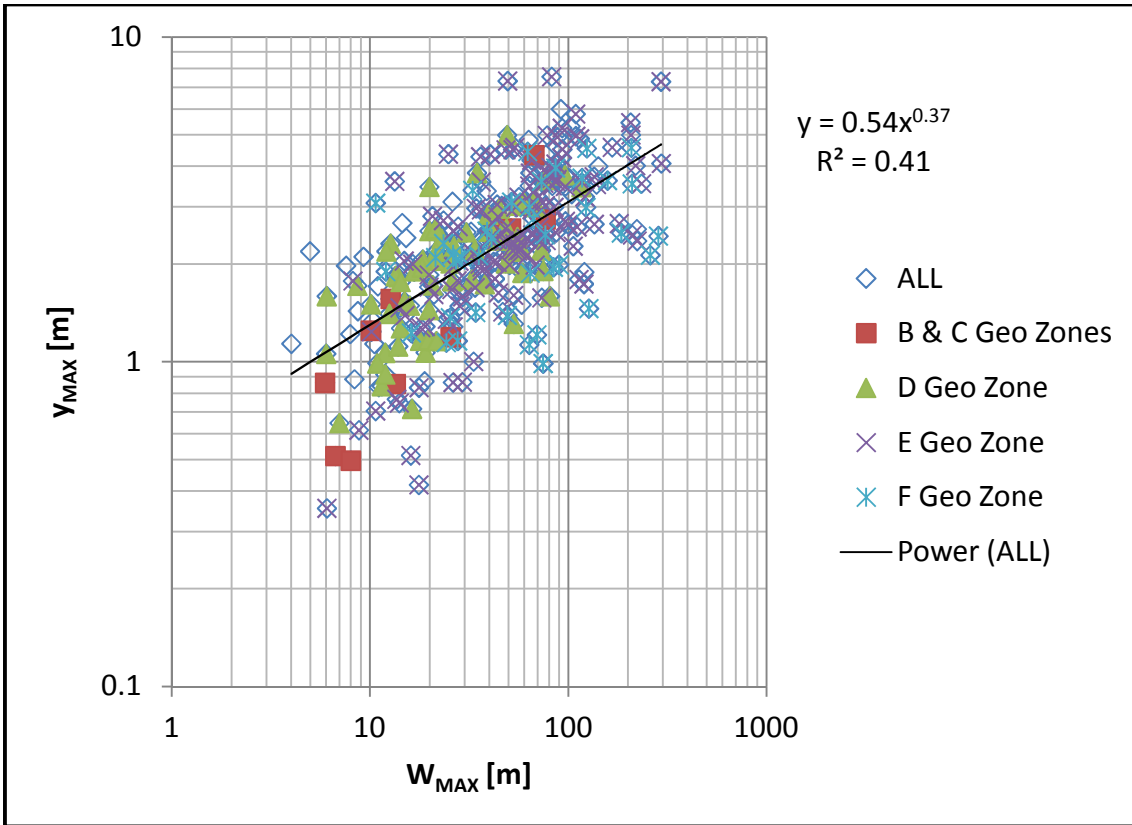


Figure 6-8 Relationship between Maximum Width ( $W_{MAX}$ ) and Maximum Flow Depth ( $y_{MAX}$ ). ALL = the entire data set

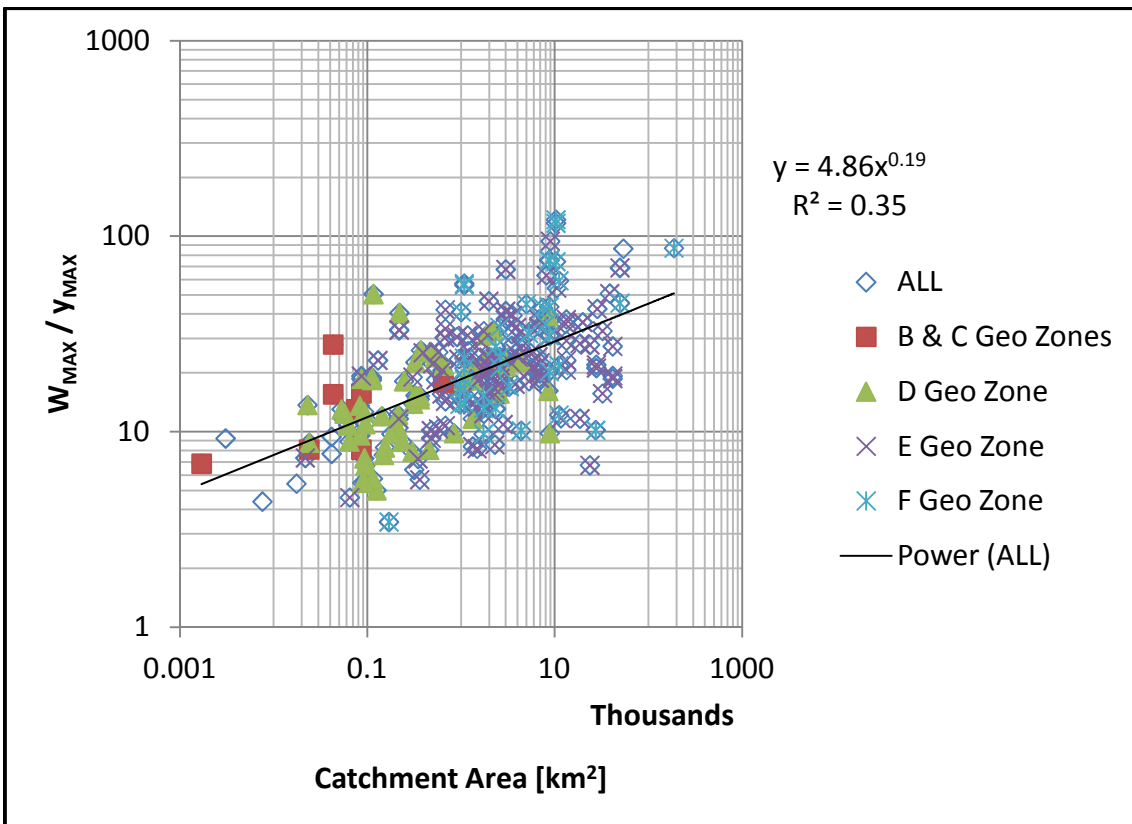


Figure 6-9 Relationship between the ratio of Maximum Width to Maximum Depth ( $W_{MAX}/y_{MAX}$ ) and Catchment Area (CA). ALL = the entire data set

## 6.4.2 Rule-based Relationships

The channel forming discharge ( $Q_c$ ), maximum width ( $W_{MAX}$ ), minimum gradient ( $S_{MIN}$ ) and channel shape parameters, have already been defined in the sections above. Therefore, the maximum depth ( $y_{MAX}$ ) can be determined by iteratively solving the Manning equation (Equation 2-2) for the depth variable.

The Manning coefficient required in determining  $y_{MAX}$  (termed the channel forming resistance coefficient,  $n_c$ ) is assumed to be a value appropriate for the channel forming discharge ( $Q_c$ ) varying from 0.025 to 0.05 for typical natural river streams. This range was obtained from Chow (1959) which consists of an extensive compilation of Manning's  $n$  values for streams and floodplains. The natural 'main channel' and 'mountain stream' Manning's  $n$  values from Chow (1959) are tabulated in Table 6-4. The Manning's  $n_c$  was categorised into Geo Zones (Table 6-5) by comparing the descriptions provided in Table 6-4 to the channel characteristic features from Table 4-1. The values in Table 6-5 were then used to calculate  $y_{MAX}$ .

**Table 6-4 Manning's  $n$  Values for Natural Main Channels and Mountain Stream from Chow (1959)**

Type of Channel and Description		Minimum	Normal	Maximum
<b>Natural Streams – Main Channels</b>				
1	Clean, straight, full, no rifts or deep pools	0.025	0.030	0.033
2	Same as #1, but more stones and weeds	0.030	0.035	0.040
3	Clean, winding, some pools and shoals	0.033	0.040	0.045
4	Same as #3, but some weeds and stones	0.035	0.045	0.050
5	Same as #4, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6	Same as #4, but more stones	0.045	0.050	0.060
7	Sluggish reaches, weed, deep pools	0.050	0.070	0.150
8	Very weed reaches, deep pools, or floodways with heavy stands of timber and brush	0.070	0.100	0.150
<b>Natural Streams – Mountain Streams, no vegetation in channel, banks usually steep, with trees and brush on banks submerged</b>				
1	Bottom: gravels, cobbles and few boulders	0.030	0.040	0.050
2	Bottom: cobble with large boulders	0.040	0.050	0.070

**Table 6-5 Channel Forming Resistance Manning's  $n_c$  According to Geo Zones**

Geo Zone	A	B	C	D	E	F
Channel Forming Manning's $n_c$	0.050	0.040	0.035	0.035	0.030	0.025

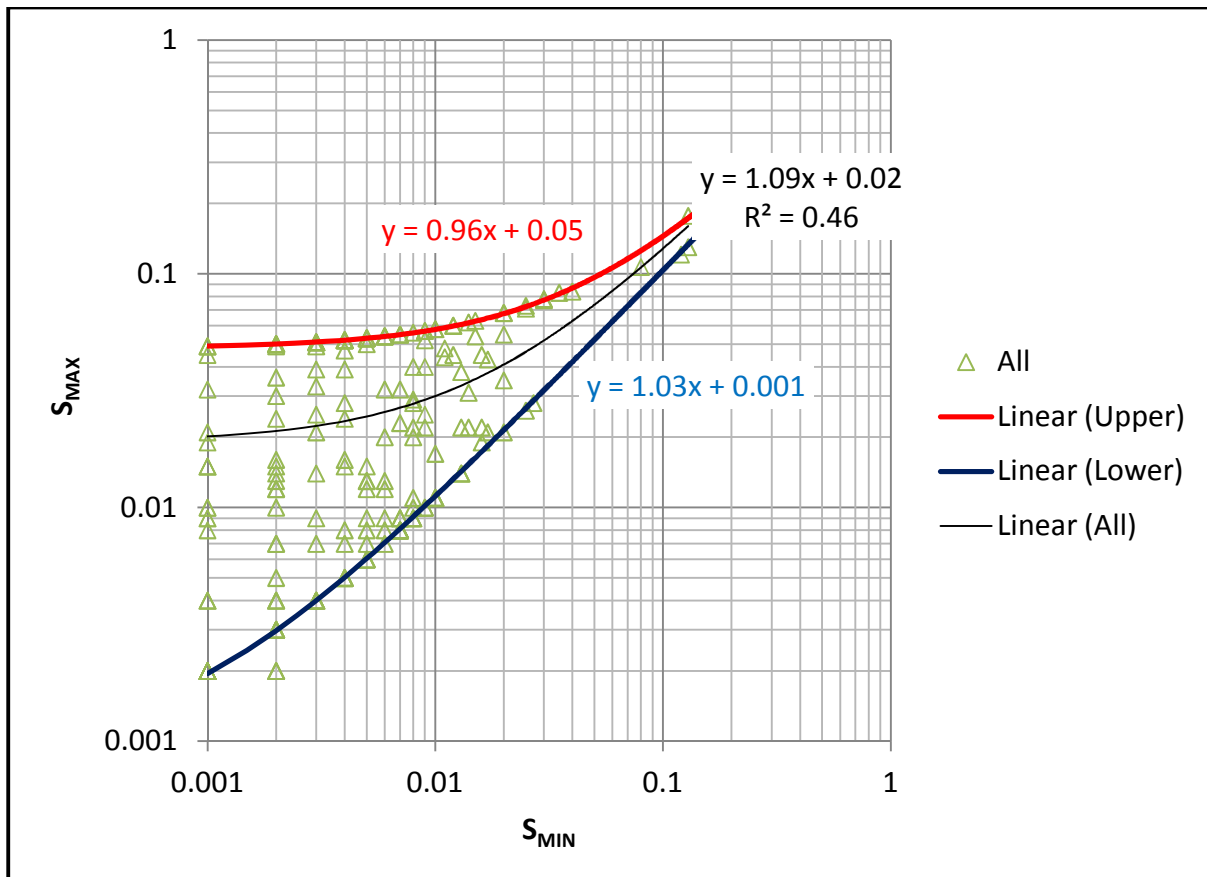
## 6.5 Maximum Gradient

### 6.5.1 Regression Relationships

During low flows, the water surface gradient in riffles and rapids is generally steeper than the valley slope. The low flow water surface gradient is required to define the low flow portion of the rating curve. In this study the low flow water gradient is termed the maximum gradient ( $S_{MAX}$ ). Figure 6-10 illustrates the relationship between the minimum gradient and maximum gradient values obtained during the estimation process. The regression relationship has been fitted to all the data points, resulting in a moderate percentage of explained variance ( $R^2 = 0.46$ ). The data points were found to be contained within two linear functions (referred to as Upper and Lower). The three relationships are tabulated in Table 6-6 and illustrated in Figure 6-10. It was unclear which relationship is applicable under different conditions and therefore how these results could be used in the hydraulic sub-model.

**Table 6-6 Maximum Gradient Relationships**

Series	Relationship	$R^2$
Regression	$S_{MAX} = 1.09(S_{MIN}) + 0.02$	0.46
Upper	$S_{MAX} = 0.96(S_{MIN}) + 0.05$	-
Lower	$S_{MAX} = 1.03(S_{MIN}) + 0.001$	-



**Figure 6-10 Relationship of Minimum Gradient ( $S_{MIN}$ ) and Maximum Gradient ( $S_{MAX}$ ). ALL = all data**

### 6.5.2 Rule-based Relationships

Linear relationships between minimum gradient ( $S_{MIN}$ ) and maximum gradient ( $S_{MAX}$ ) were obtained during the regression exercise. The data were found to be bound between two linear relationships. However, the appropriate use of a specific relationship could not be established and the estimated results were further investigated.

The lower relationship indicates that  $S_{MIN}$  and  $S_{MAX}$  are approximately equal. This condition occurs in uniform flow (i.e. the bed gradient and water surface gradient are parallel) and is generally observed in lowland rivers (Geo Zones F) which are characterised by low energy gradients and alluvial fine sediments. On the other hand, the upper relationship indicates that the  $S_{MAX}$  values are significantly higher than the  $S_{MIN}$  values indicating that these sites are characterised by high energy streams. Such streams are generally observed in mountain rivers (Geo Zones A) which are characterised by step or rapid-pool sequences. The

remaining data occurs between these two relationships and, since Geo Zones are defined by valley slope, it can be expected that the relationships for the other Geo Zones fall between the lower (Geo Zone F) and upper (Geo Zone A) relationships.

The development of the other Geo Zone (B,C,D and E) relationships were obtained by assuming they are also linear of the form:

$$S_{MAX} = qS_{MIN} + r \quad 6-3$$

where  $q$  is the slope and  $r$  is the intercept of the relationship.

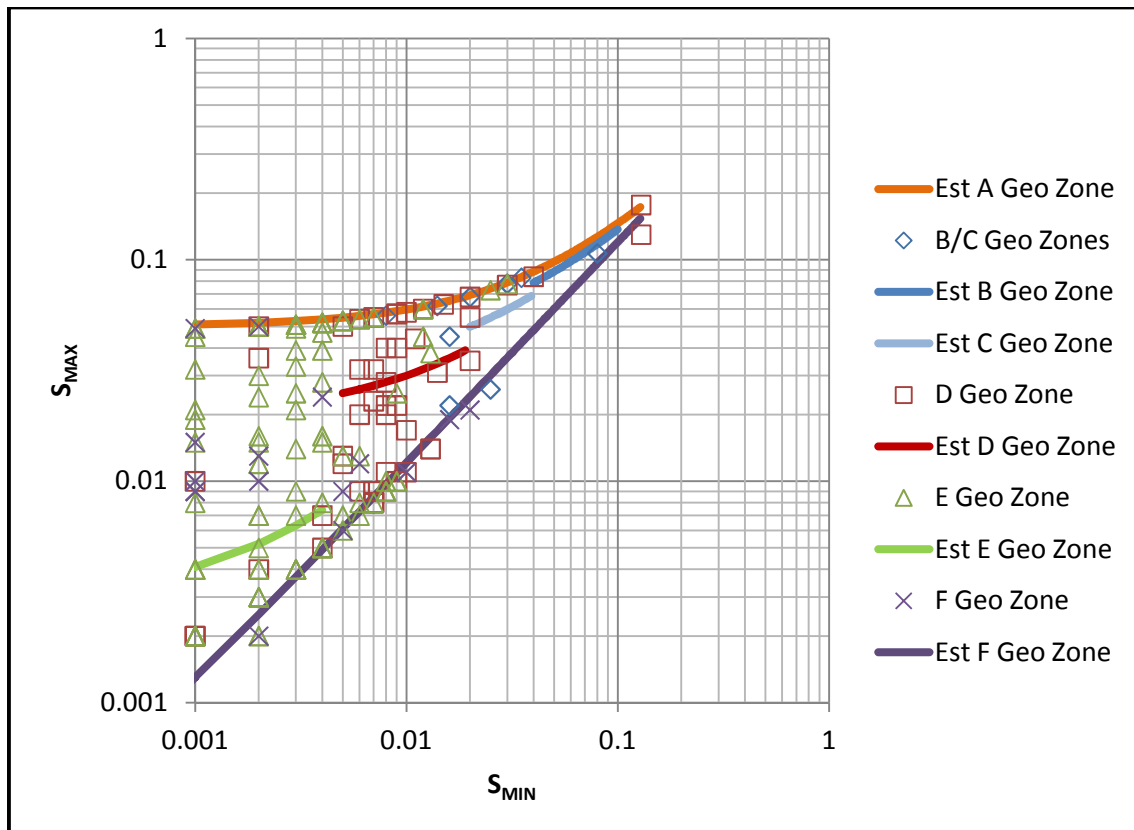
The relationships of Geo Zones A and F (Table 6-6) were plotted as log-log curves and this enabled a trend to be observed between the two. Initial slope and intercept values for Geo Zones B to E were assumed and iteratively adjusted to achieve conceptually realistic trends for each of the Geo Zones (within the limits of the valley slopes defining each zone). The adjustments of the values were partly guided by the estimated values. The slope and intercept values for the maximum gradient relationships are tabulated in Table 6-7 and the forms of the relationships and the estimated values are illustrated in Figure 6-11.

Geo Zones are based upon the valley gradient (i.e.  $S_{MIN}$ ), therefore the maximum gradient estimation equations are limited to the appropriate valley gradient ranges for the zones and these ranges are tabulated in Table 6-7.

**Table 6-7 Parameters of the Maximum Gradient Estimation Equation and Valley Gradient Ranges for Geomorphological Zones**

Geo Zone	A	B	C	D	E	F
$q$	0.05	0.04	0.03	0.02	0.003	0.0001
$r$	0.96	0.97	0.99	1.0	1.1	1.2
<b>Gradient Range *</b>	>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 6-11 Relationship of Maximum Gradient ( $S_{MAX}$ ) and Minimum Gradient ( $S_{MIN}$ ) per Geo Zone. 'Est' represents the estimated relationship.**

## 6.6 Macro Roughness

### 6.6.1 Regression 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 estimation program, macro roughness is modelled as perturbations of the basic channel shape and involves using a random number generator. Figures 6-12 and 6-13 illustrate the relationship between macro roughness and maximum flow depth ( $y_{MAX}$ ) and maximum channel width ( $W_{MAX}$ ) respectively. 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 Geo Zones (B to F). The results suggest no systematic differences between Geo Zones. Substantial scatter is observed in both series and the power relationships explain less than 50% of the variance (Table 6-8).

**Table 6-8 Macro Roughness Relationships**

Series	Relationship	R <sup>2</sup>
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 estimation process, 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 which may define benches, lateral sedimentary deposits or terraces. This action thus deviated 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 6-14, where macro roughness values of 1.0 and 0.6 were selected. Both examples have strongly correlated cross-sectional area-depth fits and the estimated profile is acceptable when compared to the observed profile. However, the estimated macro roughness values are representing the steps that are unique to the specific surveyed section, rather than what they intended to represent in the desktop hydraulic sub-model.

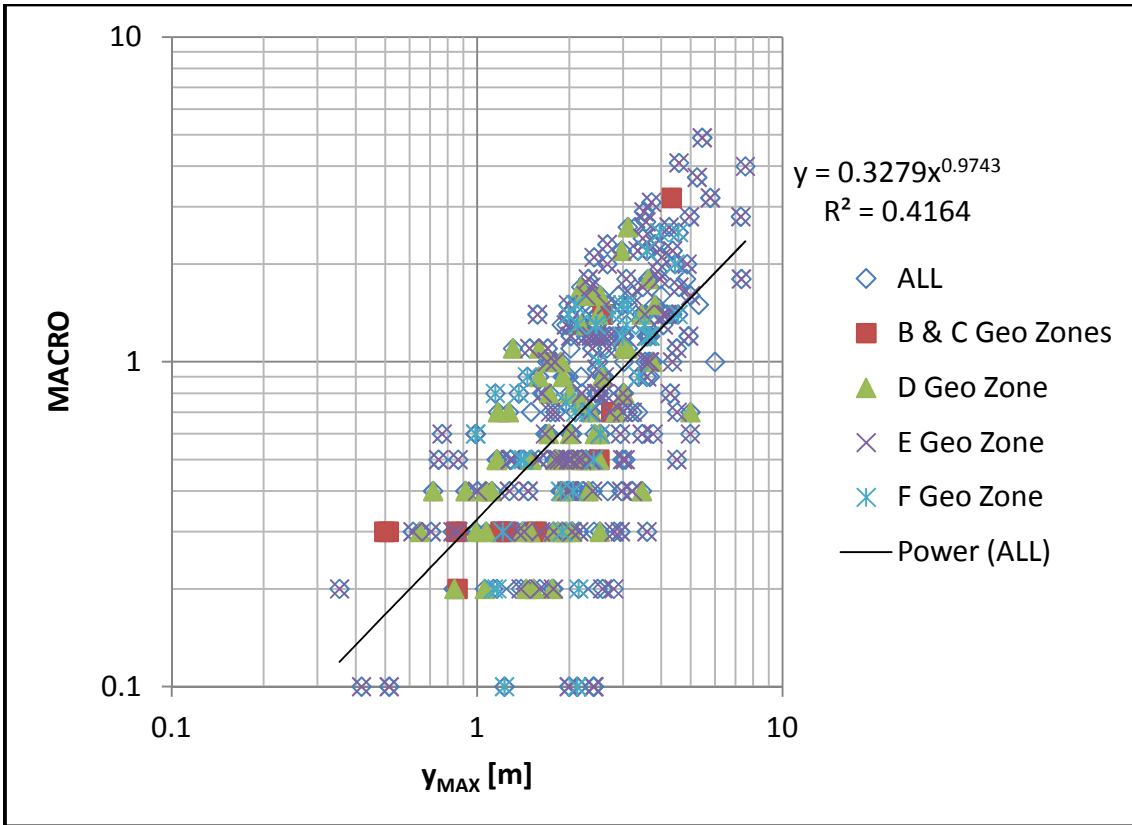


Figure 6-12 Relationship between Macro Roughness and Maximum Flow Depth ( $y_{MAX}$ ). ALL = the entire data set

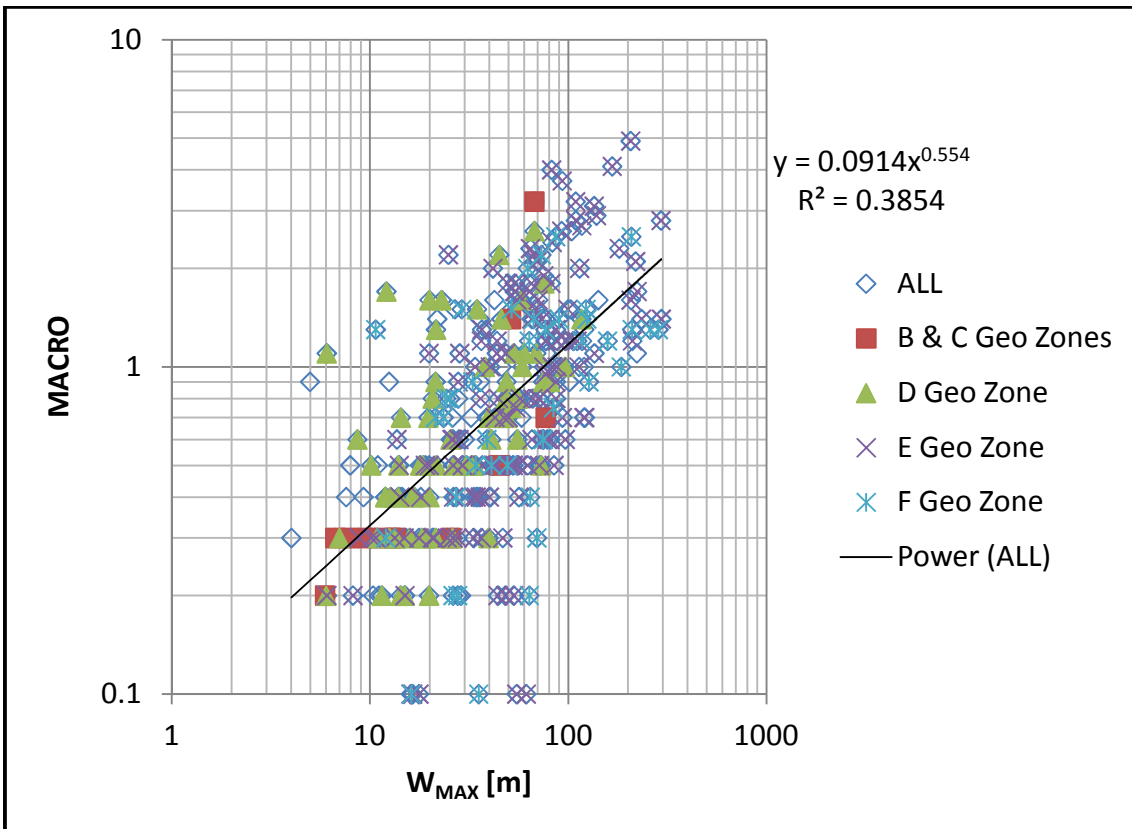
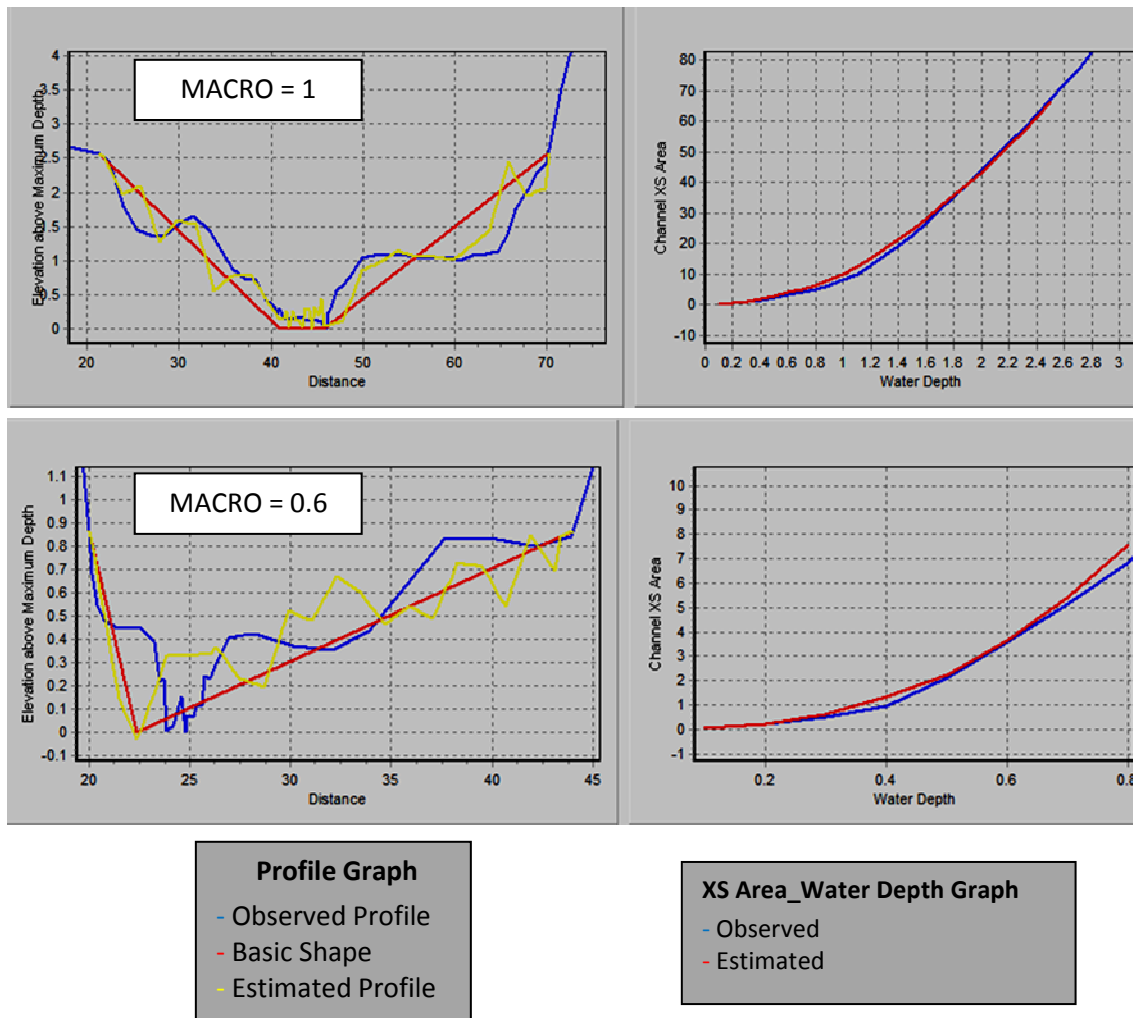


Figure 6-13 Relationship between Macro Roughness and Maximum Flow Depth ( $W_{MAX}$ ). ALL = the entire data set



**Figure 6-14 Example of Over-Estimating Macro Roughness. XS = Cross-sectional**

### 6.6.2 Rule-based Relationships

Moderately correlated power relationships were achieved for relationships between macro roughness with maximum flow depth ( $y_{MAX}$ ) and maximum channel width ( $W_{MAX}$ ). Assessing or quantifying the extent of the ‘operator error’ could not be achieved and it was ultimately assumed that the majority of the high estimated macro roughness values are over-estimates and that any relationships developed should favour the lower values.

The ratio of maximum channel width to maximum flow depth ( $\frac{W_{MAX}}{y_{MAX}}$ ) provides information about whether a channel is narrow and deep or shallow and wide. Associating this ratio to the descriptions and characteristics of Geo Zones would indicate that low ratio values would be expected in mountain rivers (Geo Zone A) and high ratios in lowland rivers (Geo Zone F).

The ratio of macro roughness to maximum flow depth ( $\frac{Macro}{y_{MAX}}$ ) provides information about

the extent of macro roughness ‘drowning’ during high flows. The ratio indicates that for the same flow depth, a high macro roughness would result in a high ratio value and conversely a low macro roughness would result in a low ratio value. Generally, high ratios of  $\frac{Macro}{y_{MAX}}$  would occur in Geo Zones A because of the presence of bedrock and boulder features and low ratio values would occur in Geo Zones F due to the dominance of fine sediment.

The two ratios were determined from the estimated values and a plot of  $\frac{W_{MAX}}{y_{MAX}}$  vs.  $\frac{Macro}{y_{MAX}}$  per Geo Zone is illustrated in Figure 6-15. Power relationships were fitted for each Geo Zone and added to the plot. A ‘fan’ type trend could be observed with the Geo Zone F relationship being the lowest curve for the high  $\frac{W_{MAX}}{y_{MAX}}$  ratio (i.e. shallow and wide) as expected. Although no data points were available for Geo Zone A, this relationship is expected to be the top curve and the other Geo Zone relationships will occur in between.

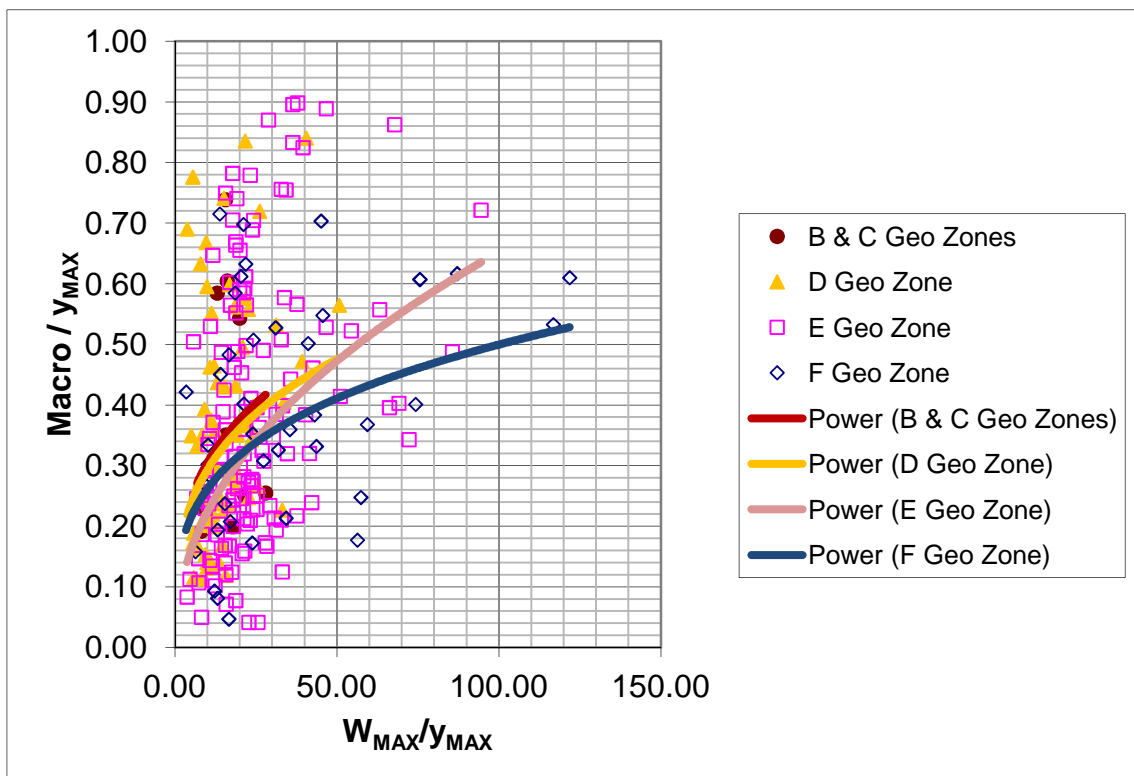


Figure 6-15 Power Relationships for the Estimated ratios of  $\frac{W_{MAX}}{y_{MAX}}$  vs.  $\frac{Macro}{y_{MAX}}$

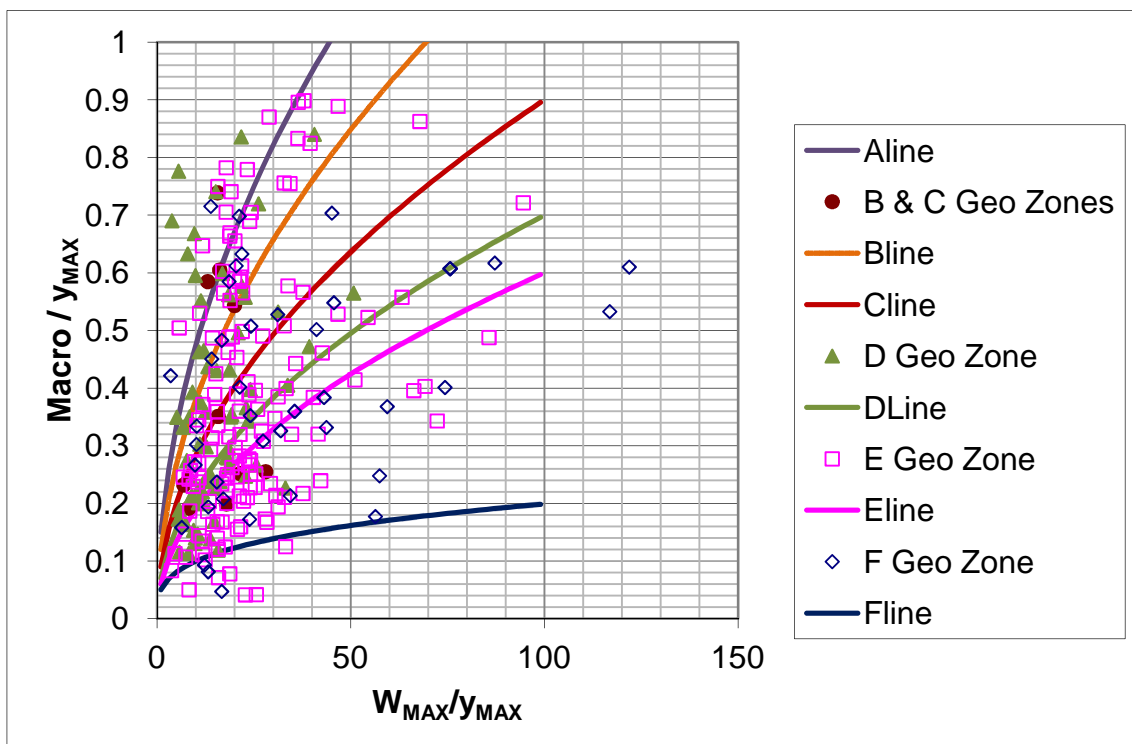
Power relationships of  $\frac{W_{MAX}}{y_{MAX}}$  vs.  $\frac{Macro}{y_{MAX}}$  for each Geo Zone were developed in the form:

$$\frac{Macro}{Y_{max}} = s \times \left( \frac{W_{max}}{Y_{max}} \right)^t \quad 6-4$$

Values for coefficients  $s$  and  $t$  are tabulated in Table 6-9 and the form of the relationships illustrated in Figure 6-16. The values of the coefficients were obtained by plotting combinations of  $s$  and  $t$  values until the relationships was visually acceptable noting that many of the Geo Zones D to F macro values were over-estimated and therefore the lower data points were favoured. The values obtained indicated that there was no change in the power coefficient value ( $s$ ) between the Geo Zones. There are insufficient data points for Geo Zones A to C and therefore it was decided to use the same power parameter and extrapolate for suitable values of the constant ( $s$ ). It was assumed that the bedrock and boulders that occur in Geo Zones A to C will have a bigger impact on the  $\frac{Macro}{y_{MAX}}$  ratio and therefore a larger difference between the constant values was estimated.

**Table 6-9 Parameters of the Macro Roughness Estimation Equation**

Geo Zone	A	B	C	D	E	F
$s$	0.15	0.12	0.09	0.07	0.06	0.05
$t$	0.50	0.50	0.50	0.50	0.50	0.50



**Figure 6-16 Relationships for the Estimation of Macro Roughness**

## 6.7 Micro Roughness

### 6.7.1 Rule-based Relationships

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 sand, gravel and cobbles. Attempts to obtain regression relationships of micro roughness using combinations or ratios of macro roughness, valley slope,  $W_{MAX}$ ,  $Y_{MAX}$ , shape and Geo Zone produced poor, non-significant, correlations ( $R^2$ : 0.15 – 0.25).

An investigation into the possibility of estimating micro roughness using sediment transport theory was therefore undertaken. A brief literature review of sediment transport pertinent to the development of a desktop hydraulic sub-model was discussed in Chapter 2, Section 2.6.4. Hack (1957) included a diagram of catchment area ( $\text{mile}^2$ ) and channel slope (ft/mile) for various median bed particle size values (mm) but the catchment area was limited to 2500  $\text{mile}^2$ . Application of Equation 2-11 for larger catchment areas produced median bed particle sizes representing cobbles and boulders and thus the Hack (1957) theory was disregarded as it does not fully represent the micro roughness definition for the RDRM.

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 use of the Hjulström curve, due to its simplicity, to determine the micro roughness. It was noted 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 was assumed to be adequate for a desktop model application. According to the Hjulström diagram (Figure 2-11) erosion, transport and deposition of a mean sediment size in a cross-section are related to the average cross-sectional velocity at a flow depth of 1m (Sinha, 1993) with distinct boundaries occurring at the points of entrainment and deposition. The micro roughness size is defined as the sediment in the channel cross-section representing sand, gravel and cobbles and is assumed to be the mean sediment size that will begin to entrain according to Hjulström (1935). The entrainment curve on the Hjulström diagram was used as the micro

roughness estimation relationship, with the following relationships synthesised from the diagram:

$$Vel_{1m} = 1.3D_s^2 + 9D_s + 14.5 \quad 14.5 < Vel_{1m} < 70 \quad 6-5$$

$$Vel_{1m} = 85.1 \ln D_s - 59.36 \quad Vel_{1m} \geq 70 \quad 6-6$$

where

$Vel_{1m}$  is the average cross-sectional velocity at a flow depth of 1m ( $cm.s^{-1}$ )

$D_s$  is the sediment size - i.e. micro roughness (mm)

The average cross-sectional velocity at a flow depth of 1m was calculated using the Manning equation (Equation 2-2). The Manning's roughness coefficient was estimated using Equation 6-7, with  $Y_{MAX}$  being equal to 1m and  $W_{MAX}$  was computed from the basic hydraulic cross-sectional shape for a depth of 1m. Uniform flow was assumed and therefore the valley slope was used as the gradient.

The parameters for Equation 6-7 for use in the micro roughness computation was done were obtained by setting  $Y_{MAX}$  equal to 1m and  $W_{MAX}$  being set equal to the width was

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).

## 6.8 Manning's Resistance Coefficients

### 6.8.1 Rule-based Relationships

Manning's  $n$  ( $n_{MIN}$  and  $n_{MAX}$ ) values are the coefficients representing the resistance of the channel and are used in the Manning equation (Equation 2-2) 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 condition (i.e.  $y_{MAX}$ ) and  $n_{MAX}$  representing the roughness coefficient during low flow condition (specifically zero depth).

Regression analyses were attempted using maximum width, maximum depth, macro roughness and micro roughness but poor correlations ( $R^2$ : 0.15 – 0.25) were achieved. Conceptual relationships (Equations 6-7 and 6-8) were subsequently developed.

The high flow Manning’s coefficient ( $n_{MIN}$ ) relationship was developed using the knowledge that Manning’s  $n$  decreases with increasing flow depth due to the relative submergence of the macro roughness elements, which will be define as  $Macro/Y_{MAX}$  (i.e. the deeper the flow compared to the macro roughness, the less the resistance to flow). Noting from Equation 6-4 that  $Macro/Y_{MAX}$  is a function of the maximum width to maximum depth ratio ( $W_{MAX}/Y_{MAX}$ ), a power relationship (Equation 6-7) was conceptualised by relating the high flow Manning’s coefficient ( $n_{MIN}$ ) to  $W_{MAX}/Y_{MAX}$ .

$$n_{MIN} = C_n \times \left( \frac{W_{MAX}}{Y_{MAX}} \right)^{P_n} \quad 6-7$$

where  $C_n$  and  $P_n$  are coefficients dependent upon the Geo Zone (Table 6-10). The coefficients were determined by iteratively adjusting the constants and powers until a good correlation with the estimated parameters was achieved.

**Table 6-10 Minimum Manning’s  $n$  Coefficients (Equation 6-7)**

Geo Zone	A	B	C	D	E	F
$C_n$	0.050	0.040	0.035	0.035	0.020	0.020
$P_n$	0.250	0.250	0.250	0.250	0.250	0.250

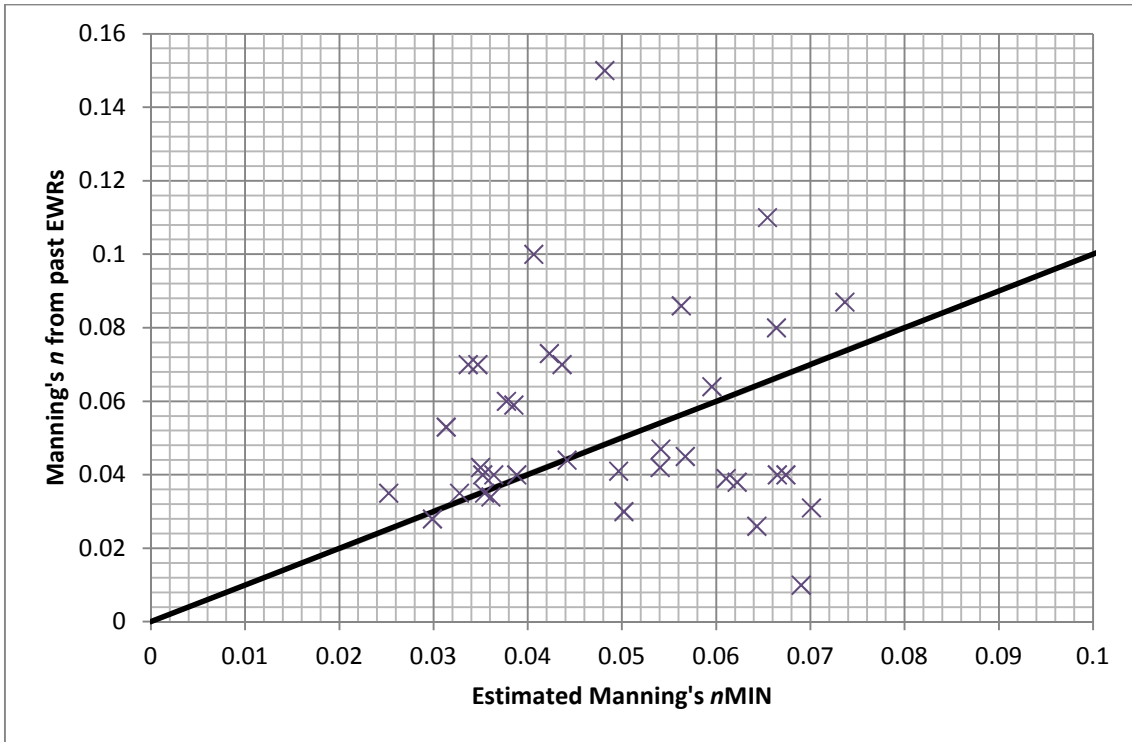
A low flow Manning’s coefficient ( $n_{MAX}$ ) relationship (Equation 6-8) was developed using the assumption that at low flows, the resistance is a combination of the macro and micro roughness, with the micro roughness having a larger influence on the resistance (i.e. form resistance is dominant). The coefficients were determined by iteratively adjusting the constants and powers until a good correlation with the estimated parameters was achieved.

$$n_{MAX} = 0.4 \times Micro^{0.5} + 0.1 \times Macro \quad 6-8$$

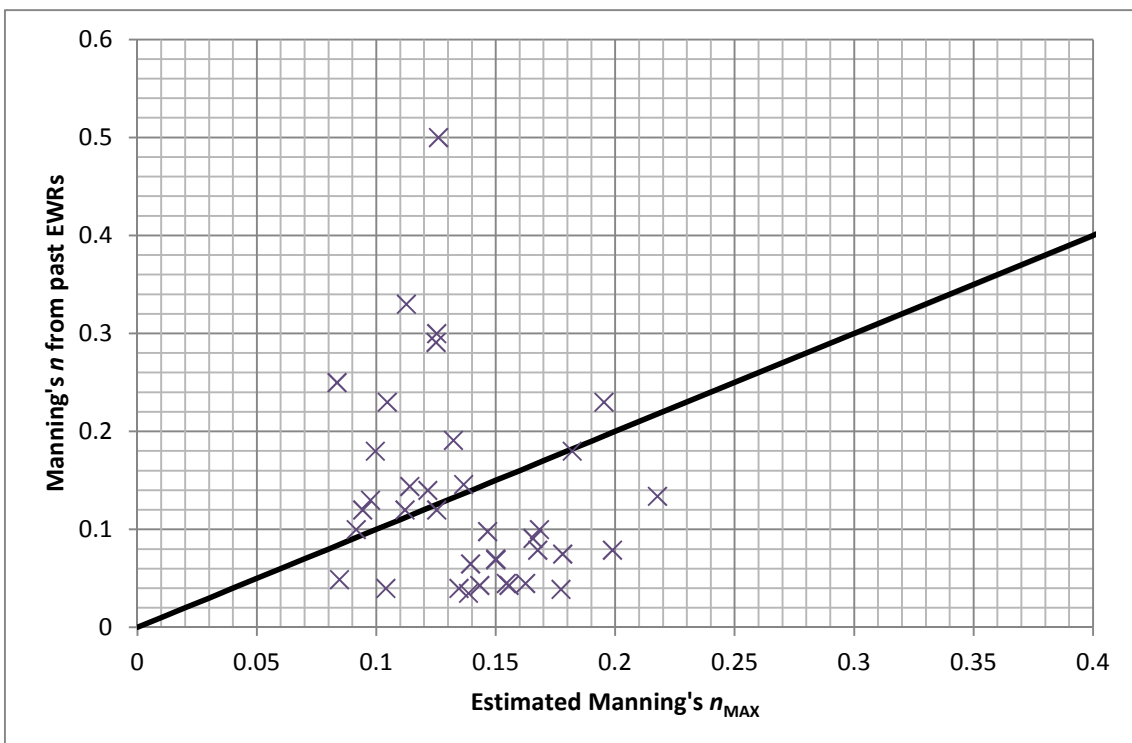
It is evident from the publications of Manning roughness coefficients (Chow, 1959; Barnes, 1967; Annable, 1996; Hicks and Mason, 1998 and Wohl and Wilcox, 2005) that maximum and minimum Manning's  $n$  values are rarely equal or similar and a limit was included to set the lowest value that  $n_{MAX}$  could be. If  $n_{MAX}$  was calculated to be less than 1.2 times  $n_{MIN}$ , the  $n_{MAX}$  value was then set to be equal to 1.2 times  $n_{MIN}$ .

The estimated Manning's coefficients from Equations 6-7 and 6-8 were thereafter compared to the coefficients from the past EWR studies found in the hydraulic database and the differences are illustrated in Figures 6-17 and 6-18. The ideal objective would be to have the estimated values equal to the hydraulic database values (i.e. an exact linear fit) and thus a 'linear' line was included in the plot to provide a visual assessment of the appropriateness of the relationships developed.

Significant scatter is observed for both relationships and it is noted that the Manning resistance coefficients are poorly estimated but, due to the complexity of the natural river processes, the sensitivity of the poor estimation could only be assessed when the rating curve is computed. This assessment was undertaken during the relationship testing phase (Chapter 7). However, the validity of the Minimum Manning's coefficient ( $n_{Min}$ ) could be achieved by comparing the estimated roughness coefficients to bankfull roughness coefficients documented in several publications and a discussion of this exercise is provided in Section 6.8.2.



**Figure 6-17** Comparison of the Minimum Manning's  $n$  relationship to high flow Manning's  $n$  from past EWR studies. The black line indicates the ideal objective (i.e. estimated value equals EWR value).



**Figure 6-18** Comparison Maximum Manning's  $n$  to low flow Manning's  $n$  from Past EWR studies. The black line indicates the ideal objective (i.e. estimated value equals EWR value).

### 6.8.2 Validation of Minimum Manning's $n$

It was possible to undertake a validation exercise of the minimum Manning's  $n$  relationship due to the availability of several international publications. The hydraulic data in these publications were used to estimate the minimum Manning resistance using Equation 6-7. The publications used were; Barnes (1967), Annable (1996), Hicks and Mason (1998) and Wohl and Wilcox (2005). Bankfull depth, bankfull width and valley slope were obtained from Barnes (1967), Annable (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 thereafter the mean annual flood was used to determine the bankfull width and bankfull depth. The valley slope was approximated to equal the frictional slope, as no valley slope information was available in Hicks and Mason (1998). All values were obtained through linear interpolation of the measured data.

These variables (maximum bankfull depth, channel width at bankfull conditions and valley slope) were used to estimate  $n_{MIN}$  using Equation 6-7 and Table 6-10. The computed estimates were then compared to the respective published Manning coefficients. A plot of the estimated  $n_{MIN}$  and published bankfull Manning coefficients is illustrated in Figure 6-19, where significant scatter is observed for all publications. Their scatter is much greater than the South African data with the overall result of the comparison being that Equation 6-7 over-estimates the minimum Manning roughness coefficient for bankfull conditions. The reasons for the over-estimates may be attributed to: (i) different bankfull definitions, (ii) the variation in bed and vegetation composition has been explicitly taken into account in the published literature but implicitly in this study, (iii) the Geo Zone based on valley slope may not be applicable to those rivers, (iv) differences in hydrology or hydrological regimes and (v) in the case of Hick and Mason (1998), the Manning coefficient used may not be a bankfull discharge resistance coefficient. The conclusion is that there remains a high degree

of unresolved uncertainty in the most appropriate method of estimating Manning's  $n$  values for a desktop model.

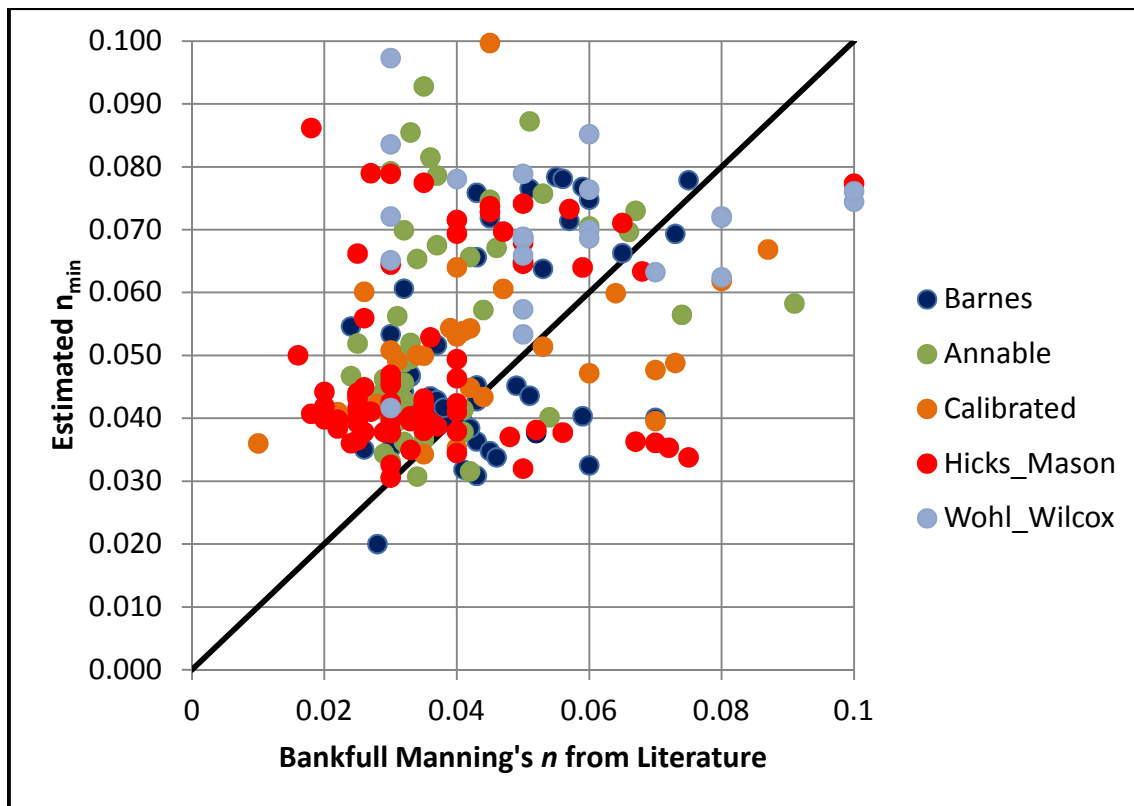


Figure 6-19 Comparison between Published Bankfull Manning coefficients and Estimated high flow Manning coefficients  $n_{MIN}$ . The black line indicates the ideal objective (i.e. estimated value equals published value).

## 6.9 Variability of Manning's $n$ and Energy Gradient with Flow Depth

### 6.9.1 Rule-based Relationships

Examining the calibrated Manning's roughness coefficients and measured energy gradients from the past EWR studies (Birkhead and Desai, in press) revealed that the Manning roughness coefficients and water surface gradients vary with flow depth. However, the rate of variation is found to differ between sites due to, amongst other variables, the variation of bed material types and channel geometry. These variations are required to be able to estimate the rating curve from zero flow depth to maximum flow depth. As the flow depth is incremented, the discharge can be calculated using the Manning equation (Equation 2-2) with the energy gradient and Manning's  $n$  computed using the defined variability value.

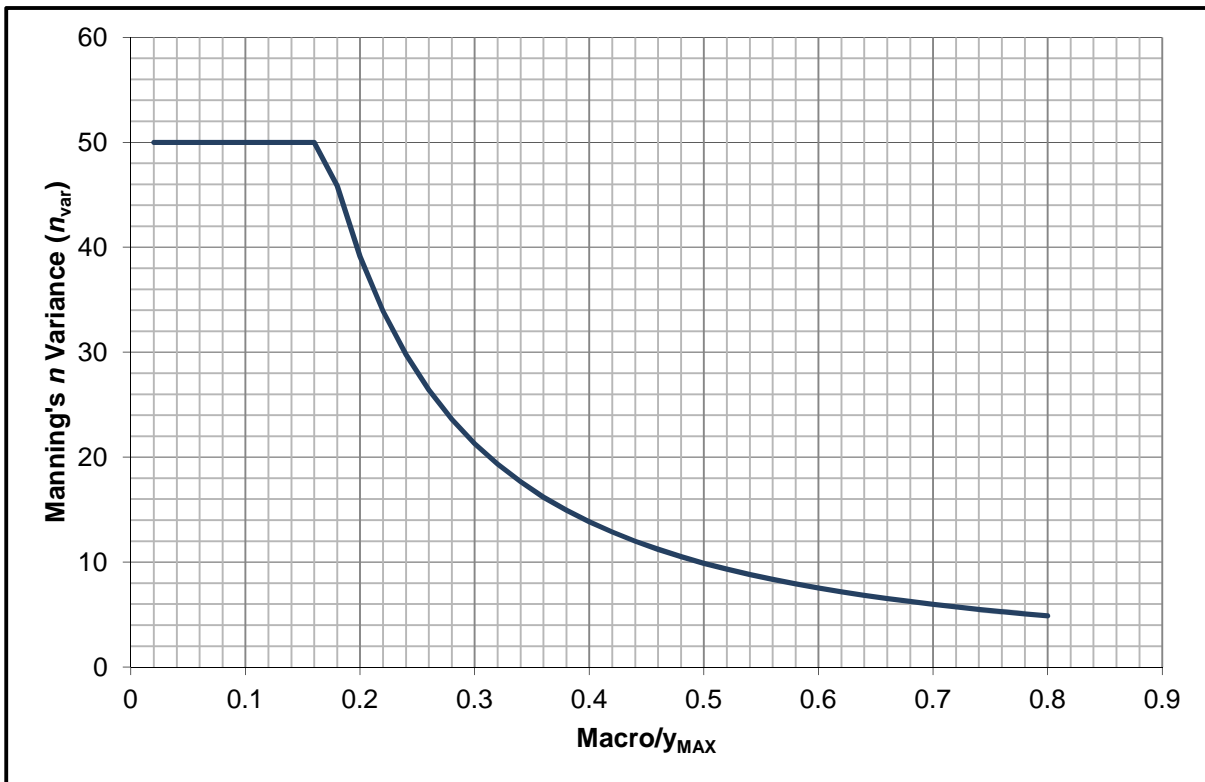
During the regression exercise, no consistent pattern could be developed to quantify the variations of the Manning roughness coefficient or the water surface gradient. At least part of the reason for this is the fact that many different parameters interact within the estimation program as discussed in earlier sections (i.e. the concept of equifinality). It was therefore necessary to determine the Manning's  $n$  and energy gradient variability parameter using conceptually sensible assumptions. It is also noted that the approaches described below are not scientifically 'accurate' but simply a pragmatic solution to an otherwise intractable problem. Further focused analyses could be undertaken to test the validity of these approaches in the future.

The S-curve shape factors incorporated into the estimation program were retained to describe the rate of change of the Manning and gradient parameters between zero depth and maximum depth (Figure 5-3). A high shape factor (a maximum of 50 was rather arbitrarily selected) suggests that small changes in the Manning coefficient will occur as the flow depth decreases from bankfull and only at very shallow depths will the Manning  $n$  values increase significantly from the minimum value toward the maximum value (Figure 5-3). This would be consistent with a low value of macro roughness (relative to maximum channel depth) such that bed resistance only plays a major role at low depths and uniform flow conditions are present for the major portion of flows. A low shape factor (a minimum of 1 was also rather arbitrarily selected) suggests that the Manning  $n/S$  values will increase as the flow depth decreases from bankfull and that the rate of increase will reduce as the water depth becomes relatively shallow (Figure 5-3). This situation would be consistent with a large relative macro roughness such that the bed resistance plays a major role in determining total channel roughness for all water depths and further represents the predominantly high energy gradients observed in large relative macro roughness situations.

The assumption was therefore made that the variability parameter for Manning's  $n$  should be defined by a relative macro roughness and the ratio of macro roughness to maximum channel depth was selected for purpose. Furthermore, a non-linear relationship has been further assumed, as it is known from the past EWR studies that the Manning's coefficient does not vary linearly with flow depth, and Equation 6-9 was developed and the form of the relationship is illustrated in Figure 6-20.

$$n_{var} = \text{Integer} \left( 3.5 \times \frac{\text{macro}^{-1.5}}{y_{max}} + 0.5 \right)$$

6-9



**Figure 6-20 Graphical Representation of Manning's  $n$  Variance (Equation 6-9)**

The energy gradient variability relationship (Equation 6-10) was developed by assuming a linear relationship and that the rate of change is dependent upon the ratio of maximum gradient to minimum gradient. When the gradients are approximately equal, the gradient value will increase from minimum gradient to maximum gradient as the flow depth decreases from bankfull and that the rate of increase will reduce as the water depth becomes relatively shallow (i.e. shape factor = 1 on, Figure 5-3). This would be consistent in situations in high energy gradients where the uniform flow is only achieved at bankfull. When the ratio is large, the gradient value will increase significantly from minimum gradient to maximum gradient only at very shallow depths (i.e. shape factor = 50, Figure 5-3) and is consistent in situations where uniform flow is observed from relatively shallow flows up to bankfull.

$$S_{VAR} = \text{Integer} \left\{ \left( 1.25 + 3.75 \times \frac{S_{MAX}}{S_{MIN}} \right) + 0.5 \right\} \quad 6-10$$

## 6.10 Discussion and Conclusions

The development of the desktop hydraulic estimation relationships for the hydraulic sub-model was achieved through combined regression and rule-based approaches, with a substantial input of what might be referred to as 'pragmatic conceptual realism'. Standard multiple regression procedures were carried out on the estimated hydraulic parameters with the regression relationships developed resulting in low to moderate correlations. It was concluded that the regression relationships developed could not be used directly to accurately represent the hydraulic characteristics for the RDRM because of the limitations and potential operator errors associated with the use of the estimation program as well as the complex interaction of the parameters. However, the regression exercise has provided valuable insight and input for the rule-based approach. The aim of the rule-based approach was to develop desktop estimation relationships that are realistic and used physical characteristics, technical theory and various assumptions using past experience gained from the literature, and was partly guided by the estimation and regression results during development.

The verification of the estimation parameters or relationships was problematic due to the complex interaction between hydraulic parameters that produce the same result for several different parameter sets. However, the minimum Manning's  $n$  relationship could be compared to international published data and over-estimated values were generally observed with differences in regional hydrological characteristics between rivers being recognised as a possible reason for the differences between the estimated and observed Manning's  $n$  coefficients.

It is noted that the values of the rule-based relationships are less than precise and in some cases set to values to achieve sensible ranges. They could therefore be considered somewhat arbitrary and difficult to justify, despite attempts to incorporate conceptual realism. The relationships were thus re-examined by comparing their results against observed hydraulic information and refined where necessary (Chapter 7).

## 7 TESTING AND REFINEMENT OF ESTIMATION RELATIONSHIPS

The hydraulic sub-model estimation relationships were tested by producing estimated cross-sectional profiles and rating curves using the estimation relationships and comparing them to observed cross-sectional profiles and rating curves. The testing was done through the development of a software program, henceforth referred to as the test program. The test program incorporated the estimation relationships developed in Chapter 6 and represented a beta-version of the hydraulic sub-model that was used in the integrated RDRM, refer to the hydraulic sub-model structures on Figures 4-1 and 4-2, but with the additional feature that the parameters could be adjusted. The parameter adjustment feature allowed for refinements to be made to the relationships where it was observed that the estimated cross-section or rating curve were majorly incorrect. The test program required the following inputs:

- **Observed Cross-sectional Profile (Elevation vs. Chainage)**
- **Observed Rating Curve (Depth vs. Flow)**
- **Geomorphological Zones (1-6)** – where 1 = Geo Zone A and 6 = Geo Zone F
- **Flood Region (1-13)** – **13 flood regions of South Africa** (Figure 2-8 and Table 2-9), Mkhundi and Kachroo (1997)
- **Hydrological Variability** – hydrological variability index as calculated in the DRM (Hughes and Hannart, 2003)
- **Valley Slope ( $\text{m.m}^{-1}$ )**
- **Catchment Area ( $\text{km}^2$ )**

As discussed in Chapter 6, the entire hydraulic database was needed to estimate the hydraulic parameters and no alternative data set could be used for the relationship testing and testing and refinement on the same data set was therefore unavoidable. However, it should be noted that the majority of the relationships that were being tested have been developed using the rule-based approach and that the hydraulic estimated parameter data set was only used as a guide, and not directly, in their development.

The testing exercise could only be undertaken for EWR sites with hydrological variability indices. Hydrological variability indices for 82 EWR sites could be obtained and represented Geo Zones D,E and F with catchment areas ranging from 20 km<sup>2</sup> to 50 000 km<sup>2</sup> and located in 7 flood regions. During the testing exercise, the hydraulic data for the most recent studies undertaken became available and were also used in the relationship testing. The following parameters are estimated and used to generate cross-sectional profiles and rating curves:

- **Mean Annual Flood ( $\bar{Q}$ )** – Equation 2.10
- **Channel Forming Discharge ( $Q_c$ )** – Equation 6.1
- **Maximum Channel Width** – Equation 6.2
- **Channel Bed Width %** - Table 6-2
- **Minimum Gradient ( $S_{MIN}$ )** – equal to Valley Slope
- **Maximum Gradient ( $S_{MAX}$ )** - Table 6-7
- **Gradient Variability** – Equation 6.10
- **Channel Forming Manning's  $n_c$**  - Table 6-5
- **Macro Roughness** - Table 6-9
- **Micro Roughness** – Equations 6-5 and 6-6
- **Minimum Manning  $n$**  – Equation 6-7
- **Maximum Manning  $n$**  – Equation 6-8
- **Manning Variability** – Equation 6-9

Statistics is generally used to assess the effect of differences of an independent variable (or variables) on the behaviour of the dependent variable. However, any attempt to use statistical analysis to assess the estimation of the hydraulic parameters using the estimation relationships was found to be inconclusive due to (i) the effects of the equifinality concept discussed in Chapter 6, (ii) the data used did not fully represent the causative factors and (iii) the same data sets being used which produced the same scatter as observed in the previous Chapters.

The accuracy of the relationships was therefore assessed, through visual comparisons and using the coefficient of efficiency values (Nash and Sutcliffe, 1970), between the estimated and observed cross-sectional area and depth relationships as well as the rating curves.

Adjustments to the parameter values were done in situations where the estimated cross-sectional profile or rating curve was not good fits. Several parameters ( $W_{MAX}$ , % Bed Width,  $y_{MAX}$ , Macro Roughness,  $n_{MIN}$  and  $n_{MAX}$ ) required adjustments and the refined relationships are discussed below.

## 7.1 Refinement of Maximum Channel Width Coefficients

The coefficients ( $C_w$  and  $P_w$ ) of the maximum width estimation,  $W_{MAX} = C_w Q_c^{P_w}$ , were adjusted in the test program until the estimated maximum width compared satisfactorily to the observed cross-section width. An increasing trend, relative to Geo Zones D, E and F, was observed for coefficient  $P_w$ , while coefficient  $C_w$  remained constant (Table 7-1). The trend was extrapolated to produce coefficients for Geo Zones A, B and C as there was insufficient information to obtain these values.

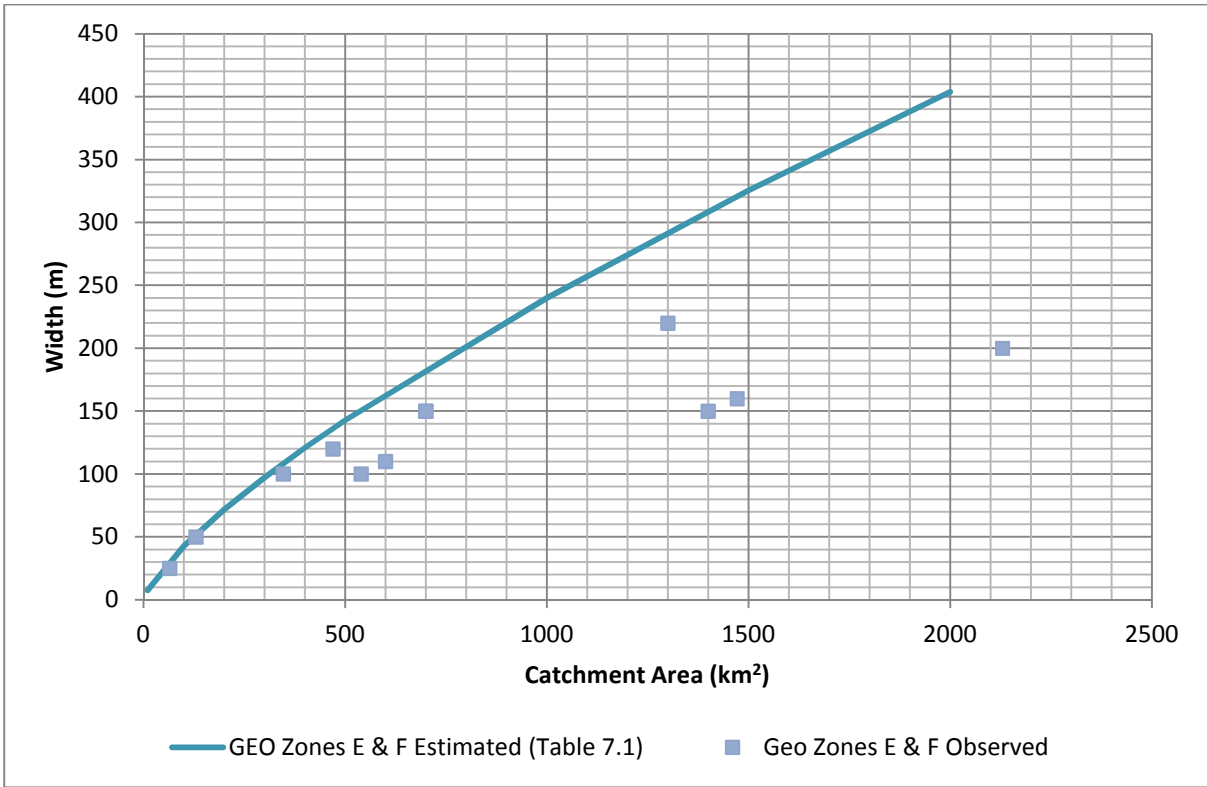
**Table 7-1 Values of Coefficient  $C_w$  and  $P_w$  for  $W_{MAX}$**

Geo Zone	A	B	C	D	E	F
$C_w$	1.35	1.35	1.35	1.35	1.35	1.35
$P_w$	0.45	0.55	0.65	0.65	0.75	0.75

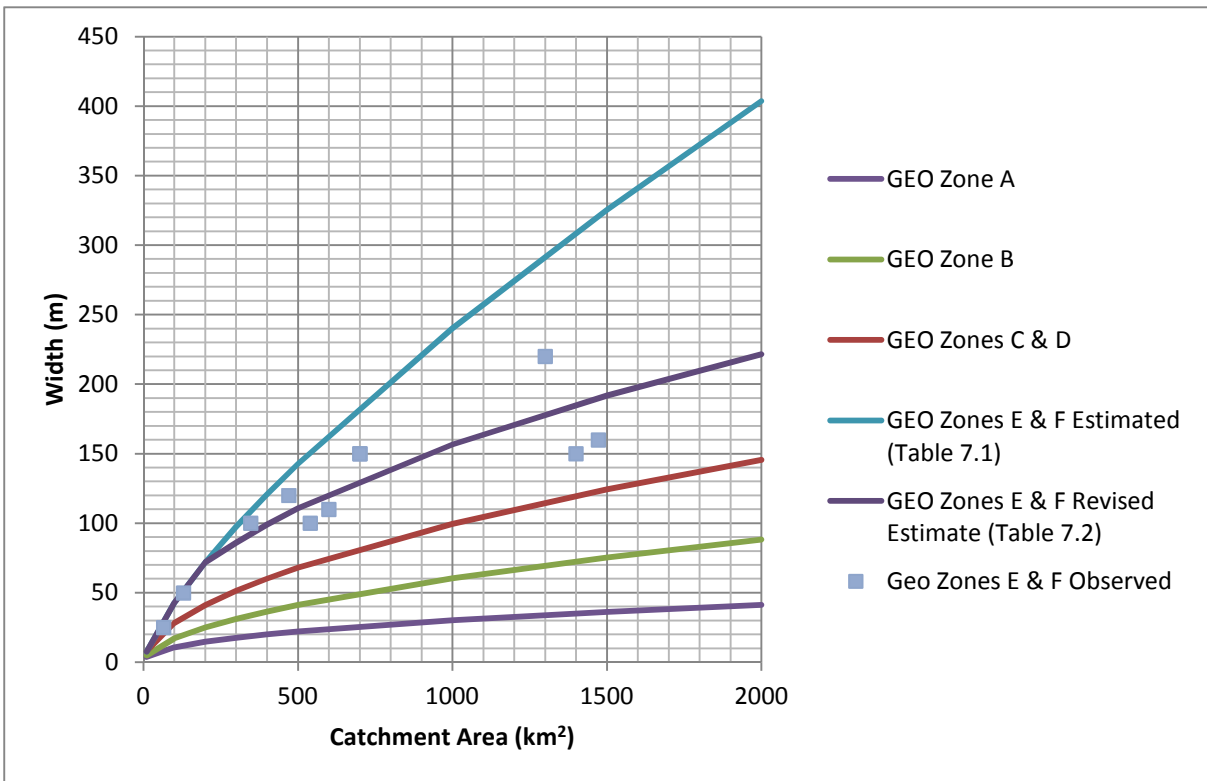
Further testing of these coefficients against the recent EWR studies hydraulic data revealed that the maximum width was being over-estimated for Geo Zones E and F (Figure 7-1). Figure 7-1 illustrates the estimated and observed maximum widths against catchment area for several Geo Zone E and F sites. It was observed that the maximum width is being over-estimated for sites with catchment areas greater than 250km<sup>2</sup>. A two-stage relationship was thus developed to estimate the maximum width for Geo Zones E and F; no change in the  $C_w$  and  $P_w$  coefficients for catchment areas less than 250 km<sup>2</sup> and additional coefficients were estimated for catchment areas greater than 250 km<sup>2</sup>. The revised coefficients are tabulated in Table 7-2 and illustrated in Figure 7-2, it is noted that coefficients for Geo Zones C and D were slightly refined during this exercise.

**Table 7-2 Revised Values of Coefficient  $C_w$  and  $P_w$  for  $W_{MAX}$**

GEO ZONE	A	B	C	D	E and F	E and F
CATCHMENT AREA (km <sup>2</sup> )	All	All	All	All	< 250	> 250
$C_w$	1.35	1.35	2.22	2.22	1.35	4.95
$P_w$	0.45	0.55	0.55	0.55	0.75	0.50



**Figure 7-1** Estimated and Observed Maximum Width based on Catchment Area for Geo Zones E and F



**Figure 7-2** Revised Maximum Width Estimation Relationships

## 7.2 Refinement of Bed Width Percentage

The testing exercise revealed that the % bed width parameter was being under-estimated for Geo Zones C, D and E. These were subsequently increased to 25%, 40% and 60% respectively.

## 7.3 Refinement of Macro Roughness

During the testing exercise, it was noticed that half the calculated macro roughness value was being plotted on the estimated cross-sectional profile, thus affecting the cross-sectional area vs. depth relationships and the rating curve. A revised random cross-section generating algorithm was included in the test program in order to better represent the estimated macro roughness. This adjustment created an additional plotting error as the number of plotting points doubles and resulted in the cross-sectional profile always being 'very rough'. However, this was not expected for foothill and lowland rivers (i.e. Geo Zones E and F). Conceptually, mountain (headwater) streams (Geo Zone A) would produce 'relatively 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 (Geo Zone F) would be 'relatively smooth' due to the low valley gradients, wide channel and fine sediment.

In order to achieve the effect of estimating 'very rough' channels in mountain streams and 'smooth' channel in lowland rivers, the ratio of macro roughness to  $y_{MAX}$  was limited according to the Geo Zone (Table 7-3) i.e. if the right hand side of Equation 6-4 was determined to be greater than the fractions listed in Table 7-3, the ratio would be set equal to the respective value listed in Table 7-3. The limits were applied to the overall macro roughness value and the effect on the other relationships dependent on macro roughness (viz.  $y_{MAX}$ ,  $n_{MIN}$  and  $n_{MAX}$ ) are also affected and were considered in the refinement process.

**Table 7-3 Maximum Ratio of Macro to  $y_{MAX}$  per Geo Zone**

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

## 7.4 Refinement of Maximum Flow Depth

The rule-based approach to estimate the maximum flow depth ( $y_{MAX}$ ) using the Manning equation (Equation 2-2) together with a simple trapezoid channel with no macro roughness, a channel forming Manning's  $n$  and maximum channel width ( $W_{MAX}$ , Equation 6-2) resulted in a general under-estimation of  $y_{MAX}$ . 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 a given set of width and depth parameters. The effects of the estimated macro roughness elements (Table 6-9) were therefore included (as part of the wetted perimeter) in the iterative Manning equation calculation for  $y_{MAX}$  (Section 6.4.2). The result was deeper channels that could accommodate the  $Q_c$ .

## 7.5 Discussion and Conclusions

The hydraulic estimation relationships were developed using regression and rule-based approaches (Chapter 6). The parameters within the relationships were at times arbitrarily set in order to produce realistic desktop hydraulic characteristics and their accuracy was assessed by comparing the results of the relationships against selected hydraulic data, results or parameters from past EWR studies. Refinements were applied to the relationships (Chapter 7) where necessary to achieve improved estimated hydraulic characteristics. The estimation program was updated with the refined estimation relationships (Table 7-4) and the revised estimated cross-sectional profiles and rating curves were compared to the observed data.

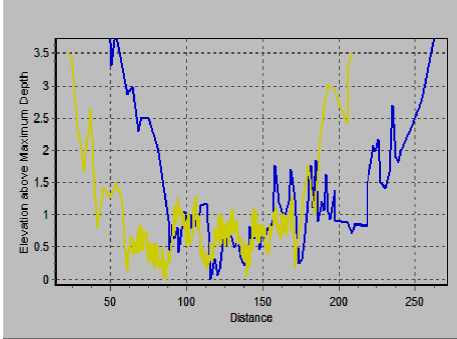
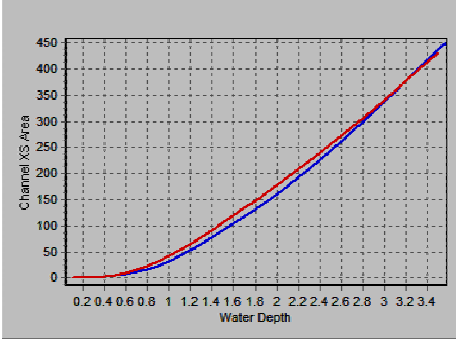
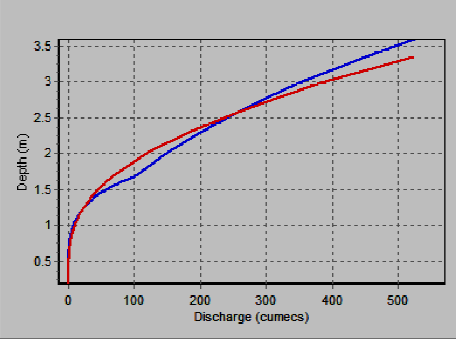
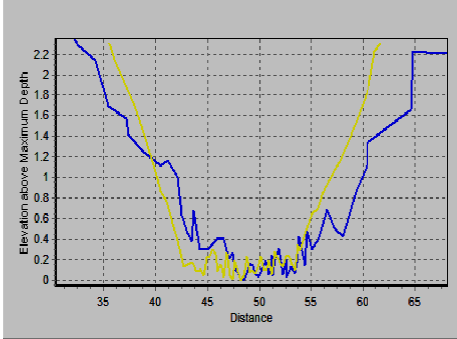
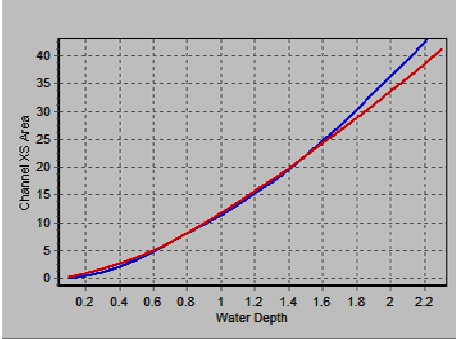
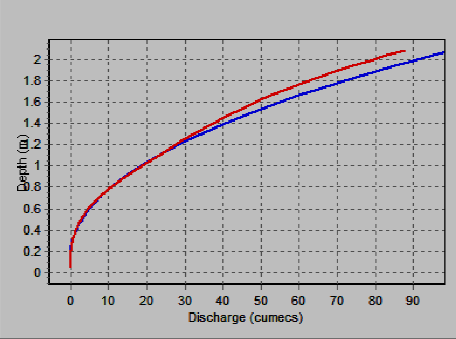
The revised estimated cross-sectional profiles and rating curves were found to be improved and five randomly selected screenshots are provided in Table 7-5 to illustrate the accuracy with which the channel geometry and hydraulic characteristics (i.e. rating curve) have been reproduced. The accuracy was assessed based upon the coefficient of efficiency and visual observations. The rating curve coefficient of efficiency is provided in Table 7-5 and ranges from 0.72 to 0.97.

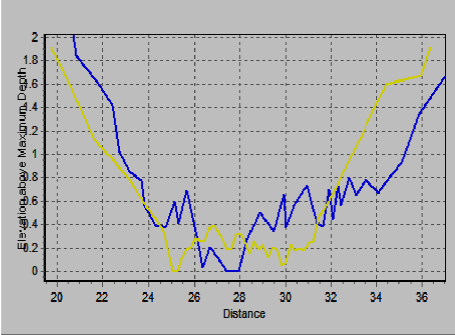
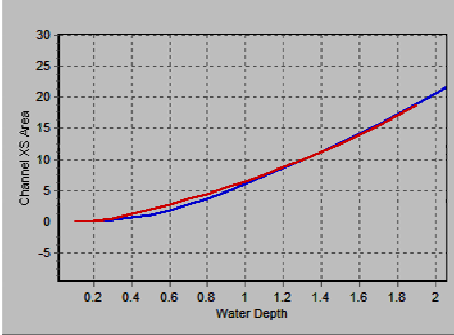
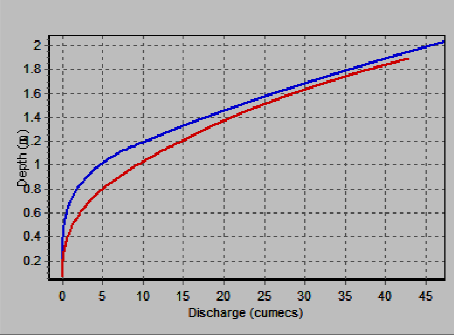
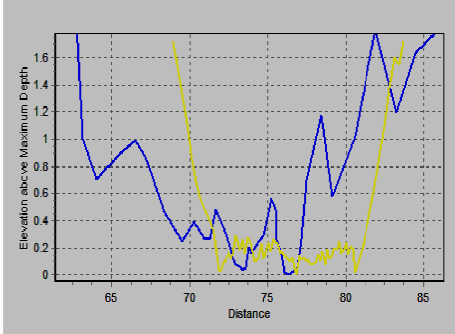
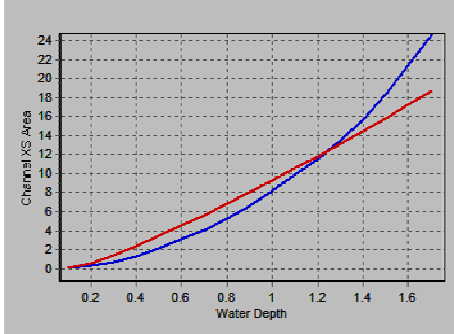
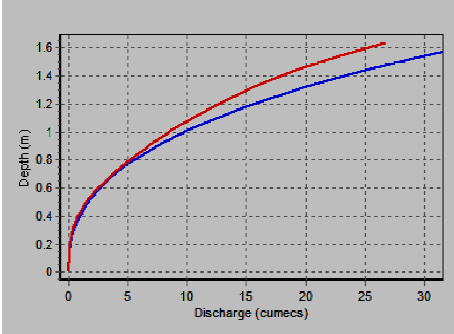
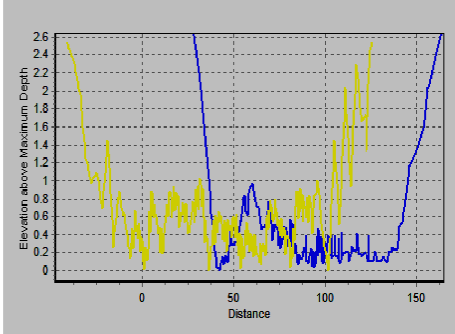
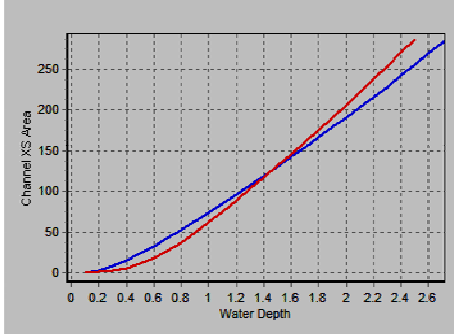
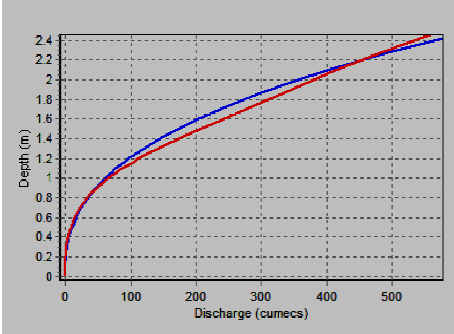
As discussed in Chapter 6, the ability to verify each of the parameters on their own is problematic because of the complex interaction between the parameters. However, the overall output of the hydraulic sub-model could be used to assess the validity of this complex model. Several past EWR sites were selected and modelled using the RDRM. The desktop outputs for these sites were thereafter compared to the outputs from past EWR ecohydraulic modelling results and the assessments are presented in Chapter 8.

**Table 7-4 Final Estimation Relationships Incorporated into the Hydraulic Sub-Model**

Parameter	Relationship	Eqn No.	Coefficients Or Constants (Per Geo Zone)						
			A	B	C	D	E	F	
Maximum Width (W <sub>MAX</sub> )	$W_{MAX} = C_w Q_c^{P_w}$	6-2	$C_w$	1.35	1.35	2.22	2.22	1.35* or 4.95#	1.35* or 4.95#
			$P_w$	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 <sub>MAX</sub> )	Use of Manning Equation – solved iteratively with other estimated parameters and channel forming Manning's $n_c$		$n_c$	0.050	0.040	0.035	0.035	0.030	0.025
Maximum Gradient (S <sub>MAX</sub> )	$S_{MAX} = qS_{MIN} + r$	6-3	$q$	0.05	0.04	0.03	0.02	0.003	0.0001
			$r$	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	$\frac{Macro}{Y_{max}} = s \times \left(\frac{W_{max}}{Y_{max}}\right)^t$	6-4	$s$	0.15	0.12	0.09	0.07	0.06	0.05
			$t$	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	$Vel_{1m} = 1.3D_s^2 + 9D_s + 14.5$ for $14.5 < Vel_{1m} < 70$	6-5							
	$Vel_{1m} = 85.1 \ln D_s - 59.36$ for $Vel_{1m} \geq 70$	6-6							
Minimum Manning n (n <sub>MIN</sub> )	$n_{Min} = C_n \times \left(\frac{W_{Max}}{Y_{Max}}\right)^{P_n}$	6-7	$C_n$	0.050	0.040	0.035	0.035	0.020	0.020
			$P_n$	0.250	0.250	0.250	0.250	0.250	0.250
Maximum Manning n (n <sub>MAX</sub> )	$n_{Max} = 0.4 \times Micro^{0.5} + 0.1 \times Macro$	6-8							
Manning n Variability	$n_{var} = Integer \left( 3.5 \times \frac{macro^{-1.5}}{y_{max}} + 0.5 \right)$	6-9							
Gradient Variability	$S_{VAR} = Integer \left\{ \left( 1.25 + 3.75 \times \frac{S_{MAX}}{S_{MIN}} \right) + 0.5 \right\}$	6-10							

**Table 7-5 Screenshots of Observed versus Estimated Cross-section Profiles and Rating Curves using the Refined Estimation Relationships. XS = Cross-sectional**

SITE NAME	CROSS-SECTIONAL PROFILE - Observed Profile - Estimated Profile	CHANNEL XS AREA VS WATER DEPTH - Observed - Estimated	RATING CURVE - Observed - Estimated
Crocodile 6	 <p>The plot shows elevation above maximum depth on the y-axis (0 to 3.5) and distance on the x-axis (0 to 250). The observed profile (yellow) and estimated profile (blue) are nearly identical, showing a channel bed that dips to a minimum of about 0.5 units between distances 100 and 150.</p>	 <p>The plot shows Channel XS Area on the y-axis (0 to 450) and Water Depth on the x-axis (0 to 3.4). Both observed (red) and estimated (blue) curves are very close, showing a non-linear increase in area with depth.</p>	 <p>The plot shows Depth (m) on the y-axis (0 to 3.5) and Discharge (cumecs) on the x-axis (0 to 500). The observed (red) and estimated (blue) curves are very close, showing a non-linear relationship between depth and discharge.</p> <p>Coefficient of Efficiency – 0.914</p>
Kromme 2	 <p>The plot shows elevation above maximum depth on the y-axis (0 to 2.2) and distance on the x-axis (0 to 65). The observed profile (yellow) and estimated profile (blue) are nearly identical, showing a channel bed that dips to a minimum of about 0.2 units between distances 45 and 55.</p>	 <p>The plot shows Channel XS Area on the y-axis (0 to 40) and Water Depth on the x-axis (0 to 2.2). Both observed (red) and estimated (blue) curves are very close, showing a non-linear increase in area with depth.</p>	 <p>The plot shows Depth (m) on the y-axis (0 to 2) and Discharge (cumecs) on the x-axis (0 to 90). The observed (red) and estimated (blue) curves are very close, showing a non-linear relationship between depth and discharge.</p> <p>Coefficient of Efficiency – 0.923</p>

SITE NAME	CROSS-SECTIONAL PROFILE - Observed Profile - Estimated Profile	CHANNEL XS AREA VS WATER DEPTH - Observed - Estimated	RATING CURVE - Observed - Estimated
Sabie_Sand 1			 <p>Coefficient of Efficiency – 0.727</p>
Sabie_Sand 7			 <p>Coefficient of Efficiency – 0.967</p>
Vaal 4			 <p>Coefficient of Efficiency – 0.922</p>

## **8 ANALYSIS OF RESULTS FROM THE HYDRAULIC SUB-MODEL AND THE REVISED DESKTOP RESERVE MODEL**

Desktop hydraulic relationships were developed using combinations of regression and rule-based approaches (Chapters 6 and 7) and involved several testing and refinement processes. It was concluded that the relationships tabulated in Table 7-4 produce hydraulic results with an acceptable level of uncertainty for a desktop application and were therefore appropriate for inclusion into the hydraulic sub-model of the RDRM. However, it was also considered necessary to further investigate the different uncertainties that result from using the combination of simplified hydraulic parameter estimation equations, as well as investigating the sensitivity of both the hydraulic sub-model and the overall EWR estimates from the integrated RDRM model to these uncertainties. These investigations were based on a subset of the previous EWR studies for which detailed hydraulic and habitat data were available.

One of the sources of uncertainty is the structure of the hydraulic sub-model as expressed through the various relationships given in Table 7-4. These uncertainties are inevitable in any environmental model, of which the hydraulic model is an example, and are the result of simplifications of complex interactions that are difficult to uniquely identify from the limited amount of observed data that are available. This is related to the problem of equifinality that has already been referred to. Additional sources of uncertainty are associated with the 'input' parameters that ultimately force the model algorithms for any specific site:

- The estimate of a suitable channel forming discharge using the flood estimations procedures of Mkhundi and Kachroo (1997). The amount of observed stream flow data used in the Mkhundi and Kachroo (1997) study was very limited and subject to typical errors associated with measuring extreme flows. Any regional flood assessment of this type will therefore be subject to quite large uncertainties which will be propagated into

the maximum width estimate of the hydraulic sub-model – a parameter value upon which many other parts of the model are very dependent.

- The selection of an appropriate Geo Zone is also subject to uncertainty, as are the valley slope limits that have been defined for the different Geo Zones. This source of uncertainty is difficult to quantify but could be associated with spatial scale issues. For example, a specific Geo Zone may be considered appropriate for a site based on the characteristics of a river reach extending over several 100s of metres or more. However, the specific site that is selected for use within a workshop may have very local characteristics that are different to what might be expected for the reach as a whole. This issue has been recognised in many previous EWR studies and is partly related to the method of field site selection using a cross-section that is considered ecologically sensitive, rather than one that might be representative of the reach as a whole (Birkhead, 2010). It would be very difficult to reproduce the same type of effect within a desktop estimation model and therefore the RDRM is expected to generate channel cross-section and hydraulic characteristics that are representative of a reach.
- The hydrology sub-model is used to provide the maximum baseflow values (for the main wet and dry season months) based on a mathematical hydrograph separation approach using regional values (Hughes *et al.*, 2003) and a specific % point on the flow duration curve of the separated baseflows. Both the separation method and the selection of a suitable % point value (20% by default) are subject to uncertainty and will influence the reference discharge used to calculate the available habitat at zero ecological stress within the hydraulic sub-model (see Chapter 3).

It is therefore apparent that simple comparisons between the hydraulic and habitat characteristics generated using field surveyed channel cross-sections (EWR workshop results) and those generated by the hydraulic sub-model will always be expected to reveal differences. However, there are no other available data that can be used to assess the outputs of the hydraulic sub-model and whether it can be considered an appropriate

estimation method. The approach that has been adopted here is to quantify the differences in hydraulic characteristics between the workshop and desktop model results, but also to try and identify the possible reasons for these differences and whether or not they are critical from the point of view of the usefulness of the hydraulic sub-model and the integrated RDRM. These assessments involved three main steps:

1. The habitat (velocity-depth) class (Table 8-1) distributions that are generated by the hydraulic sub-model, and used by the ecological sub-model, are compared with the outputs from a number of Rapid III, Intermediate and Comprehensive ER determinations (workshop results) that included detailed channel cross-section surveys and hydraulic analyses.
2. The differences between the workshop and desktop results are examined to identify possible reasons for differences and/or similarity.
3. The effects of some changes to the uncertain input parameters on the habitat class distributions are examined in an attempt to identify the components of the model that are most sensitive to input uncertainties.
4. Similar comparisons and sensitivity analyses are performed using the differences in the workshop and desktop estimates of the annual EWR for the recommended level of ecological protection established during the workshops.

The objective is therefore to assess the overall applicability of the hydraulic sub-model, as well as the sensitivity of the outputs to uncertain inputs. The term 'applicability' has been used here as opposed to accuracy because the model is not expected to be able to 'accurately' reproduce an observed channel cross-section or its exact hydraulic characteristics. The objective is for the model to produce representative (for a given type and size of river) hydraulic characteristics. Sections 8.1 to 8.3 describe the methods that have been used to perform the comparisons, while sections 8.4 and 8.5 discuss the results. All of the detailed diagrams for each of the sites used in the comparative study are presented in Appendix B.

**Table 8-1 Flow or Habitat Class Definitions used in the RDRM**

Flow Class	Velocity		Depth	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit
<b>SvS</b>	0.0	0.3	0.0	0.1
<b>SS</b>	0.0	0.3	0.1	0.5
<b>SD</b>	0.0	0.3	0.5	N/A
<b>FvS</b>	0.3	N/A	0.0	0.1
<b>FS</b>	0.3	N/A	0.1	0.2
<b>FI</b>	0.3	N/A	0.2	0.3
<b>FD</b>	0.3	N/A	0.3	N/A

### **8.1 Comparison of Flow Class Distributions**

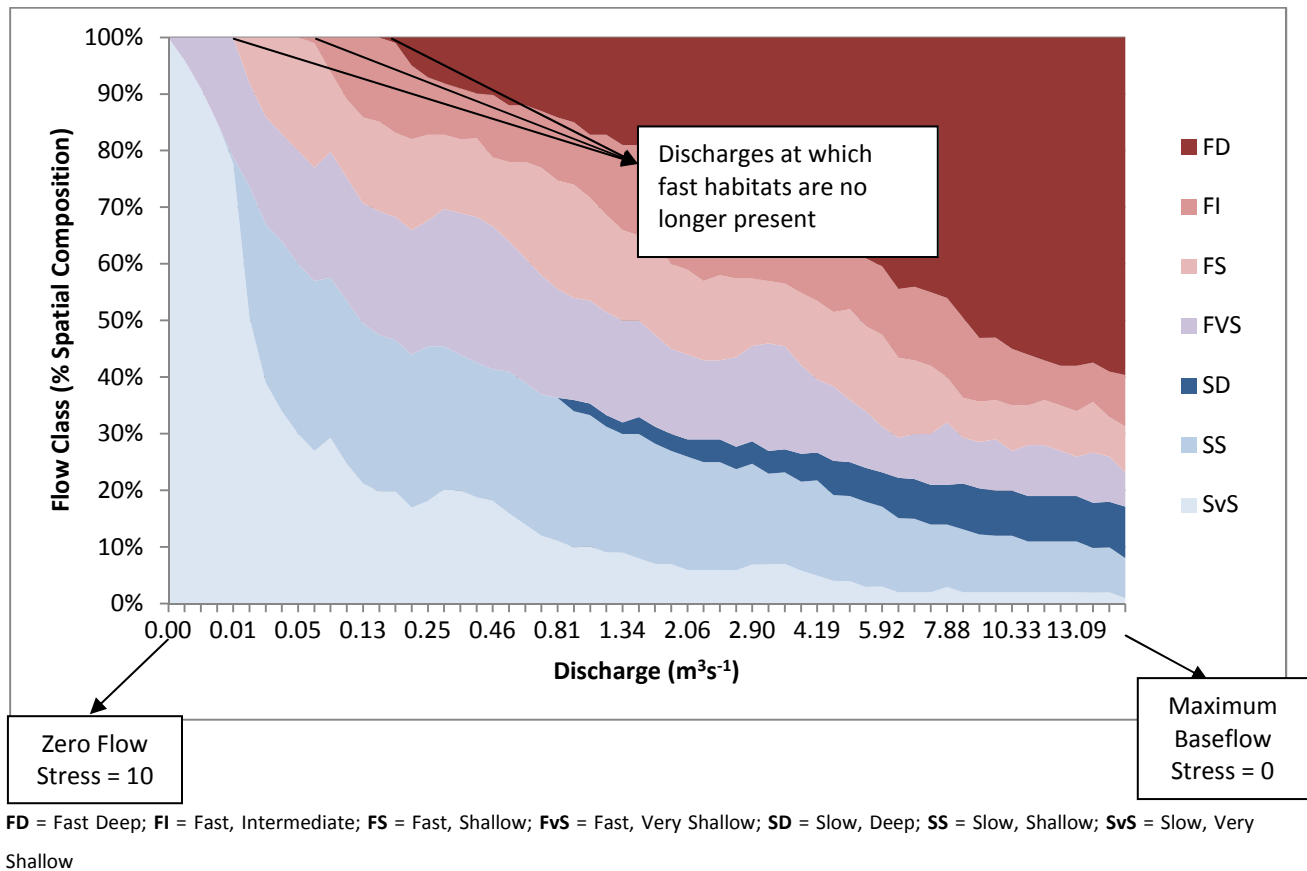
As discussed in Sections 2.4.1 and 2.5, distributions of flow classes (Table 8-1) and how these vary with discharge are used to specify preference habitats in terms of hydraulic variables and these are used by ecologists in SA to assist in the quantification of EWRs (Birkhead, 2010; Hughes and Louw, 2010). The ecological sub-model generates stress-flow relationships using the variation in the distributions of flow classes with changes in discharge computed by the hydraulic sub-model. The basis for estimating stress is the reduction in the frequencies of the flow classes coupled with the assumption that a stress of zero is associated with the maximum baseflow discharge, while zero flow represents a stress of 10, as discussed in Chapter 3. Thus, an assessment of the applicability of the hydraulic sub-model can be achieved by comparing flow class frequencies computed in past EWR studies (referred to as Workshop FC) with the frequencies resulting from the estimated desktop hydraulics (referred to as Desktop FC). Similarities between the workshop and desktop FCs would infer that the hydraulic sub-model is sufficiently capable of reproducing representative hydraulic conditions. To avoid unnecessary repetition of the phrase “workshop and desktop”, the abbreviations “W” and “D” are used henceforth.

The most important hydraulic habitat characteristics are the frequencies of the fast-deep (FD), fast-intermediate (FI) and fast-shallow (FS) habitats, as these three FCs are used to determine the stress-flow relationships in the ecological sub-model (Chapter 3). Given the approach used in the RDRM (and EWR workshops) to estimating the stress-flow relationships, it is therefore the rate at which these FCs decline with discharge, as well as the discharge at which they disappear that is important.

The workshop FCs are based on the surveyed channel cross-sections and estimated hydraulic parameters and computed using the HABFLO model (HABitat FLOW Simulation – developed by Hirschowitz et al, 2007). The workshop FC data have been received from hydraulic practitioners involved in ER determination studies. Desktop hydraulic conditions were generated at the locations of the past EWR sites using the RDRM in conjunction with the default desktop parameters for all three sub-models (hydrological, hydraulic and ecological). The desktop hydraulic conditions (cross-sectional profile, maximum flow depth, maximum and minimum Manning's n, maximum and minimum water surface gradient, macro roughness and maximum baseflow discharge) were then used as inputs into the HABFLO model to generate the desktop FCs. Some of the input information required for the desktop hydraulic model (specifically the Geo Zone and valley slope) was obtained from the hydraulic database (Birkhead and Desai, in press), while the default flood region and associated parameters were used to calculate channel forming discharge. In all cases the default hydrological sub-model inputs were retained i.e. the regional parameters of the hydrograph separation approach and the 20th percentile of the baseflow flow duration curve to quantify the maximum baseflow.

The FC frequency distributions are presented (Tables 8-2 to 8-5) as stacked area plots relating discharge in the channel with the frequencies of the 7 flow classes and an example is illustrated in Figure 8-1. The horizontal axes represent the flow rate ( $\text{m}^3 \text{s}^{-1}$ ) and the vertical axes represent the percentage of the wetted cross section occupied by each of the 7 different fish FCs (Section 2.5). In order to present the area plots in a manner that one may be able to easily observe the similarities and differences, the x- and y-axis labels and x-axis values are not shown in the

remaining FC frequency graphs presented in this thesis. It should be noted that the x-axis values range from zero flow up to the maximum baseflow discharge for each particular site (defined using the natural hydrology time series within the hydrology sub-model of the RDRM), as illustrated in Figure 8-1. The points at which the habitats disappear are also shown in Figure 8-1.



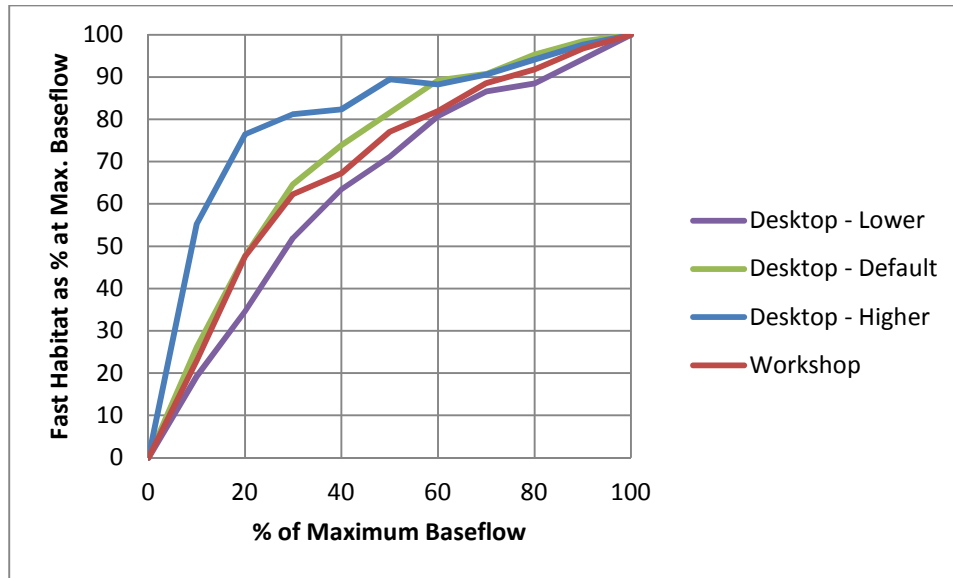
**Figure 8-1 Example of an Area Plot of Flow Classes**

Visual comparisons of the W and D FC distributions (Table 8-2 to 8-5) indicate that the hydraulic sub-model has the capability to reproduce representative hydraulic conditions for some locations around SA, while for other sites the desktop FCs were found to be dissimilar compared to the workshop. It became clear that these differences required further investigation using more quantitative comparison methods. It is understood from discussions with EWR ecology specialists at many workshops that the frequency distribution of each fast FC

is not very important for a desktop application and that the critical issues are (i) the amount of all (or any) fast habitats and (ii) the relative rate of change at which the fast habitats decline with decreasing discharge (from maximum baseflow to zero). These generally accepted concepts have therefore been used to develop more appropriate and quantitative measures of comparison between the W and D FCs.

The area under the curve of all the fast habitats was obtained by determining the integral of the total fast habitats (FS, FI and FD) for both the W and D FC frequency distributions. These % frequency-discharge areas (henceforth referred to habitat areas) are used as a surrogate to specify the abundance of fast habitats available. The percentage difference between the habitat areas for the W and D results indicates how much more or less fast habitat is computed for the full range of discharges between zero and the estimated maximum baseflow.

To quantify the relative rate of change in the fast habitats, the frequency of the total fast FCs for all discharges (zero to maximum baseflow) were computed as percentages of the FC frequency at maximum baseflow (see example in Figure 8-2). The differences in these percentages between the W and D results represent the differences in the rate at which the fast habitat classes decline with declining discharge. The plots can be interpreted by comparing the workshop rate of change to the desktop rate of changes for each Geo Zone, for example in Figure 8-2 the workshop, default and lower Geo Zone rates of changes are similar while the higher Geo Zone desktop result has a much slower rate of change for higher discharges followed by a very rapid rate of change at lower flows.



**Figure 8-2 Example of Rate of Change Plot (Lower, Default and Higher refer to the different Geo Zones used in the simulations)**

## **8.2 Sensitivity of Flow Class Distributions to Parameter Changes**

This part of the assessment includes some evaluations of how the flow class distributions generated by the desktop hydraulic sub-model change (together with comparisons with the workshop result) with changes in some of the uncertain parameters. Specifically, it has been noted that occasionally the default Geo Zone obtained from the geomorphological database (Moolman, 2008) and estimated valley slope were incompatible. Geo Zones are related to specific valley slope ranges and if the valley slope value does not coincide with the stipulated Geo Zone gradient range, they are identified in the algorithm as being incompatible and either the slope or the Geo Zone must be changed. These incompatibilities could occur due to the differences in resolutions used or because the sites were selected in a reach that is locally steeper or shallower than the overall valley slope of the area. The desktop results were therefore re-generated using Geo Zones that were one higher and one lower than the database Geo Zone and the comparisons with the workshop results repeated.

A limited number of additional sensitivity tests were undertaken using different values for the % point on the baseflow duration curve (part of the hydrology sub-model output) to estimate the maximum baseflow, as well as tests using different channel forming discharges (modified by selecting a different flood region).

### **8.3 Comparisons and sensitivity of final EWR results**

The final set of comparisons are based on the EWR results (expressed as the total mean annual low flow requirement as a percentage of the natural mean annual runoff) generated by the workshop and the integrated RDRM. The workshop EWR results are sometimes affected by the use of additional information about the present day state of the river (e.g. change in hydrological seasonality or impacts which are not related to changes in the flow regime of the river) which will not be available for a desktop level estimation. Therefore not all of the workshop EWR requirements can be compared to the desktop EWR results and where these issues were noted in the workshop reports those sites were excluded from the comparison of EWR results.

It is also recognised that the sensitivity of the integrated RDRM results can be related to the methods and data used within all three of the main sub-models (hydrological, hydraulic and ecological). It is therefore quite possible that there are some parameters of the hydraulic sub-model that cause substantial changes to the flow classes distributions, but do not make much difference to the final EWR results (and vice versa). These differences in sensitivity between the main hydraulic sub-model outputs and the final EWR results could also be dependent upon some site specific hydrology or hydraulic conditions. This set of comparisons are therefore designed to shed further light on the importance of the issues of uncertainty and parameter sensitivity of the hydraulic sub-model, relative to the outputs of the RDRM as a whole.

## **8.4 Presentation of Workshop and Desktop Comparisons**

Fifteen sites were selected to assess the hydraulic sub-model in terms of the FCs it produced. These sites were selected on the basis that (i) workshop FCs are available, (ii) EWR results based on the FS-R or HFS-R methodology, (iii) workshop results were not affected by present day state of the rivers as discussed in Section 8.3 and (iv) they cover a relatively wide range of conditions in terms of climate zone, geomorphology zone and river size. The sites were categorised into Geo Zones and the area plots of the W and D FCs are tabulated together with summary observations of the differences in Tables 8-2 to 8-5.

The assessments were undertaken using 15 sites consisting of 1 B, 2 C, 4 D, 4 E and 4 F default Geo Zones, default Geo Zone refers to the Geo Zone obtained from the geomorphological database. The list of sites and the default Geo Zones, valley slope, catchment area and channel forming discharge are provided in Table 8-6, together with information on whether the default Geo Zone is compatible with the valley slope or not. A further comment is provided for the sites where the valley slope is close to the limit of the gradients (upper or lower) for a particular Geo Zone.

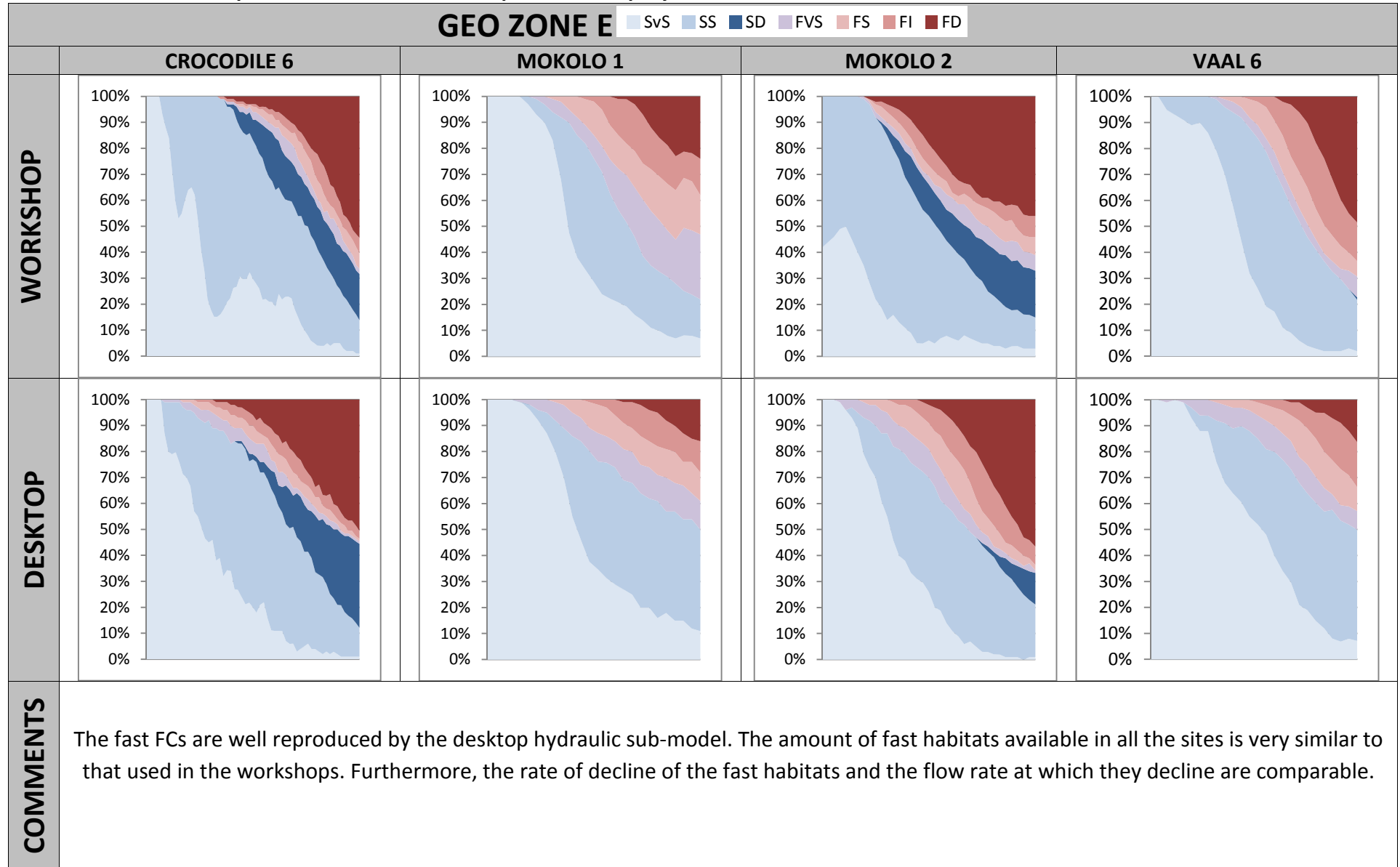
Table 8-2 Comparisons between Workshop and Desktop Hydraulic Habitat Results for Geo Zones B and C

GEO ZONE B AND C			
<span style="color: lightblue;">■</span> SvS <span style="color: blue;">■</span> SS <span style="color: darkblue;">■</span> SD <span style="color: purple;">■</span> FVS <span style="color: pink;">■</span> FS <span style="color: red;">■</span> FI <span style="color: darkred;">■</span> FD			
	E3BLY (Blytaanspruit)	E6SAB (Sabaan)	E9LON (Lone Creek)
WORKSHOP			
DESKTOP			
COMMENTS	Desktop results simulate more fast shallow habitat. The rates of decline are similar in both W/D results.	Desktop results simulate more fast shallow and little fast deep habitat. The rates of decline are similar with FI and FS habitats.	Desktop results simulate more fast habitats and the fast habitats are lost at lower flow rates in the desktop results.
	Overall, more fast habitats are estimated by the hydraulic sub-model, with the rate of decline and the flow rates at which the habitat classes disappear lower than the workshop results.		

**Table 8-3 Comparisons between Workshop and Desktop Hydraulic Habitat Results for Geo Zone D**

<b>GEO ZONE D</b>				
<span style="color: lightblue;">■</span> SvS <span style="color: blue;">■</span> SS <span style="color: darkblue;">■</span> SD <span style="color: purple;">■</span> FVS <span style="color: pink;">■</span> FS <span style="color: red;">■</span> FI <span style="color: darkred;">■</span> FD				
	<b>CROCODILE 1</b>	<b>CROCODILE 7</b>	<b>SABIE 4</b>	<b>SABIE 5</b>
<b>WORKSHOP</b>				
<b>DESKTOP</b>				
<b>COMMENTS</b>	<p>Crocodile 7, Sabie 4 and Sabie 5 desktop and workshop results produce similar fast habits, a bit more or less in certain cases but acceptable within the expected ranges of uncertainty. The rate at which each habitat is lost and the flow depths at which they cease to exist are also similar except for Crocodile1, where the workshop results indicate a decrease in fast habitat at higher flow rates. This is due to the observed cross-sectional profile being a narrow deep channel, with near vertical banks up to 1.4m and thereafter the banks changes to near horizontal topography. Crocodile1 has a unique topography that has not been catered for in the hydraulic sub-model.</p>			

**Table 8-4 Comparisons between Workshop and Desktop Hydraulic Habitat Results for Geo Zone E**



**Table 8-5 Comparisons between Workshop and Desktop Hydraulic Habitat Results for Geo Zone F**

<b>GEO ZONE F</b>				
<span style="color: lightblue;">■</span> SvS <span style="color: blue;">■</span> SS <span style="color: darkblue;">■</span> SD <span style="color: purple;">■</span> FVS <span style="color: pink;">■</span> FS <span style="color: red;">■</span> FI <span style="color: darkred;">■</span> FD				
	<b>ORANGE 6</b>	<b>ORANGE 7</b>	<b>VAAL 2</b>	<b>VAAL 8</b>
<b>WORKSHOP</b>				
<b>DESKTOP</b>				
<b>COMMENTS</b>	<p>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 being generated by the hydraulic sub-model. 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.</p>			

**Table 8-6 List of Sites Used in the Comparison of Workshop and Desktop Flow Classes and EWRs**

Site Name	Default Geo Zone	Valley Slope (VS)	Geo Zone Compatibility comments	Geo Zone according to VS	Channel Forming Discharge ( $Q_c, m^3 s^{-1}$ )	Catchment Area ( $km^2$ )
E9LON – Lone Creek River (Sabie)	B	0.0200	NO	C	6.7	24
E3BLY – Blytaanspruit (Crocodile)	C	0.0150	NO	D	16.2	76
6SAB – Sabaan (Sabie)	C	0.0170	NO	D	17.8	86
CROC1 - Valyspruit (Crocodile)	D	0.0087	YES		640.4	8675
CROC7 – Kaap (Crocodile)	D	0.0083	YES		145.5	1340
SAB4 – Mac Mac (Sabie_Sand)	D	0.0240	YES, borderline between D and C		27.2	150
SAB5 – Marite (Sabie_Sand)	D	0.0080	YES		66.1	476
CROC6 – Knongoma (Crocodile)	E	0.0017	YES, borderline between E and F		705.5	10490
MOK1 – Vaalwater (Mokolo)	E	0.0040	YES, borderline between E and D		155.5	1633
MOK2 – Tobacco Farm (Mokolo)	E	0.0033	YES		103.6	3825
VAAL6 – Klip (Vaal)	E	0.0038	YES		157.9	1730
ORAN6 – Caledon (Orange)	F	0.0009	YES		1518.7	20493
ORAN7 – Kraai (Orange)	F	0.0027	NO	E	958.3	8675
VAAL2 – Grootdraai (Vaal)	F	0.0010	YES, borderline between F and E		314.1	7995
VAAL8 – Bavaria (Vaal)	F	0.0007	YES		299.7	7503

The FC distributions, rate of fast habitat change graphs and simulated channel cross-sections using the default Geo Zones as well as one higher and one lower (except when the default zone is F) are presented in Appendix B. The objective of including alternative Geo Zones is to illustrate the sensitivity of the hydraulic sub-model outputs to this parameter. The habitat areas of the W and D fast habitats calculated, along with the percentage differences of the habitat areas between the W and D are tabulated in Table 8-7. The percentage differences between workshop and the desktop fast FC habitat areas are further illustrated as bar graphs in Figure 8-3. Table 8-7 also includes the recommended levels of protection determined in the workshops (REC), the workshop EWR results (specified as the

total mean annual requirement as a percentage of the natural mean annual runoff) and the desktop EWR estimates for different Geo Zones. The EWRs are illustrated as bar graphs in Figure 8-4 and the maximum percentage difference calculated between W and D requirements are shown above each set of bars. Figure 8-5 compares the EWRs for the higher and lower Geo Zones as a fraction of the EWR for the default Geo Zone. The workshop EWR results, as well as any other information relating to their determination, were obtained from DWA (2010a, 2010b and 2010c) and Louw and Koekemoer (2011).

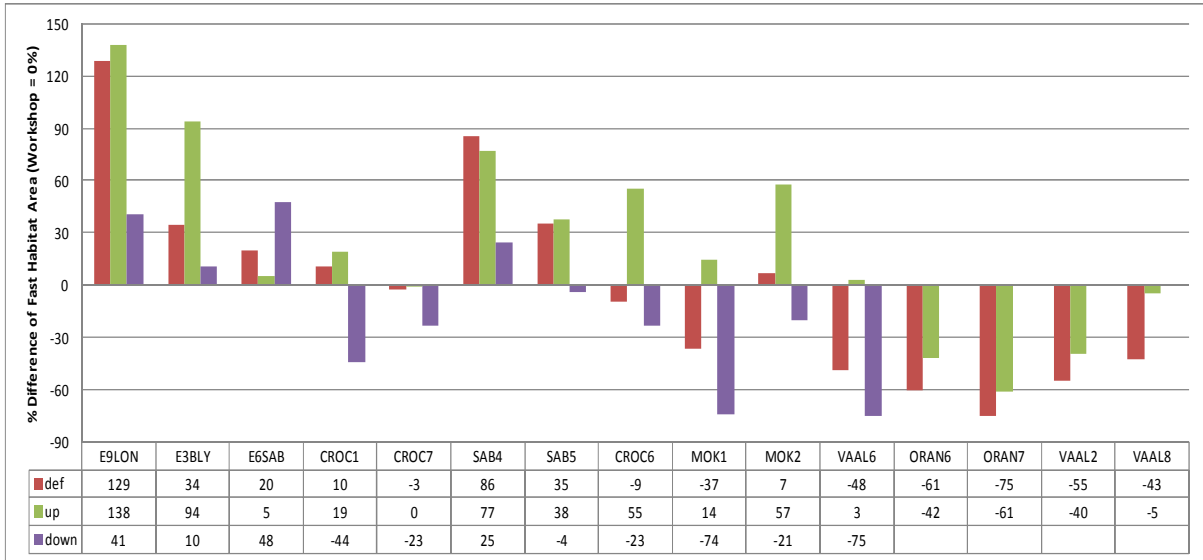
The differences between the rate of change in the workshop and desktop fast habitats at specific percentages of maximum baseflow are tabulated in Table 8-8. The percentage differences of the EWR flow requirements and the FC areas given in Table 8-7 are repeated in Table 8-8 for ease of comparison. The graphical plots of the rate of change of the fast habitats are provided in detail in Appendix B.

Each of the 15 sites was evaluated in detail using the information presented in Appendix B, Tables 8-7 and 8-8 and Figures 8-3 to 8-5. During the evaluations the effects of additional sources of uncertainty in the parameters of the hydraulic sub-model were assessed and are discussed in the following section. The two other main potential sources of uncertainty are the % point of the baseflow duration curve used to define maximum baseflow and the channel forming discharge that is used to estimate maximum channel width.

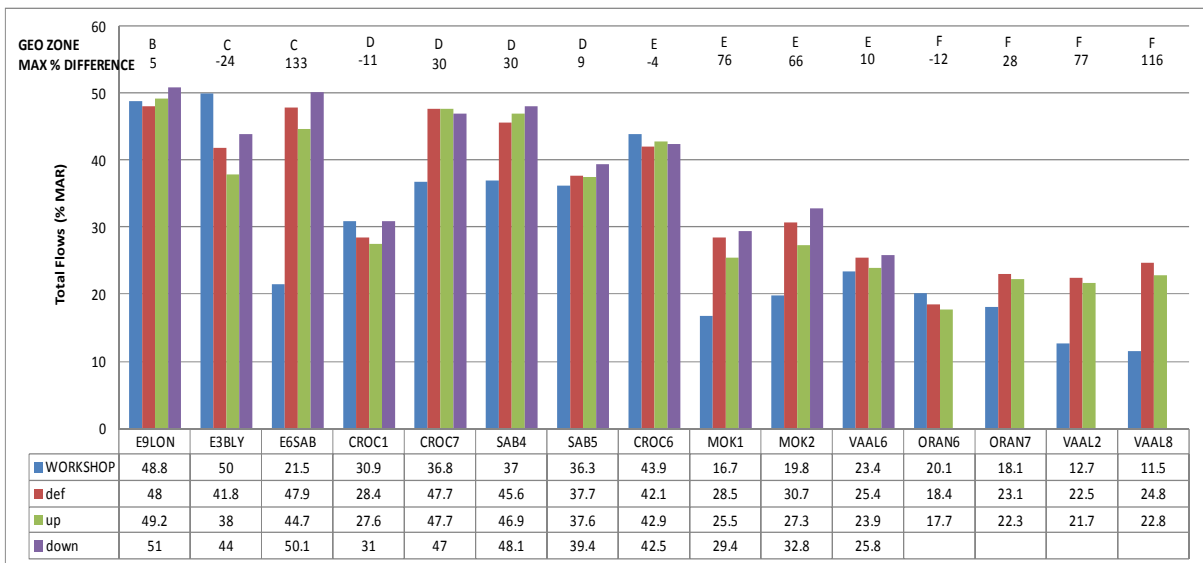
**Table 8-7 Workshop and Desktop Comparisons – comparing the Fast Habitat Areas and the EWR Flow Requirements**

Site Name	Geo Zone	Fast Habitat Area – Workshop	Fast Habitat Area - Desktop	% Difference of Fast Habitat Area '-' indicates that the estimate is less	Workshop - REC	Total Flow Requirement - % MAR - WORKSHOP	Total Flow Requirement - % MAR - DESKTOP	% Difference of Total Flow Requirement '-' indicates that the estimate is less
<b>E9LON – Lone Creek River (Sabie)</b>	Higher – A		22.10	138	B		49.2	1
	Default – B	9.30	21.28	129		48.8	48.0	-2
	Lower – C		13.10	41			51.0	5
<b>E3BLY – Blytaanspruit (Crocodile)</b>	Higher – B		30.50	94	B		38.0	-24
	Default – C	15.74	21.13	34		50.0	41.8	-16
	Lower – D		17.38	10			44.0	-12
<b>E6SAB – Sabaan (Sabie)</b>	Higher – B		17.30	5	B		44.7	108
	Default – C	16.45	19.74	20		21.5	47.9	123
	Lower – D		24.29	48			50.1	133
<b>CROC1 - Valyspruit (Crocodile)</b>	Higher – C		1014.90	19	A/B		27.6	-11
	Default – D	849.52	938.67	10		30.9	28.4	-8
	Lower – E		475.91	-44			31.0	0
<b>CROC7 – Kaap (Crocodile)</b>	Higher – C		3243.92	0	B		47.7	30
	Default – D	3250.08	3159.23	-3		36.8	47.7	30
	Lower – E		2489.80	-23			47.0	28
<b>SAB4 – Mac Mac (Sabie_Sand)</b>	Higher – C		116.88	77	A/B		46.9	27
	Default – D	66.19	122.86	86		37.0	45.6	23
	Lower – E		82.61	25			48.1	30
<b>SAB5 – Marite (Sabie_Sand)</b>	Higher – C		381.29	38	B		37.6	4
	Default – D	277.08	374.18	35		36.3	37.7	4
	Lower – E		265.28	-4			39.4	9

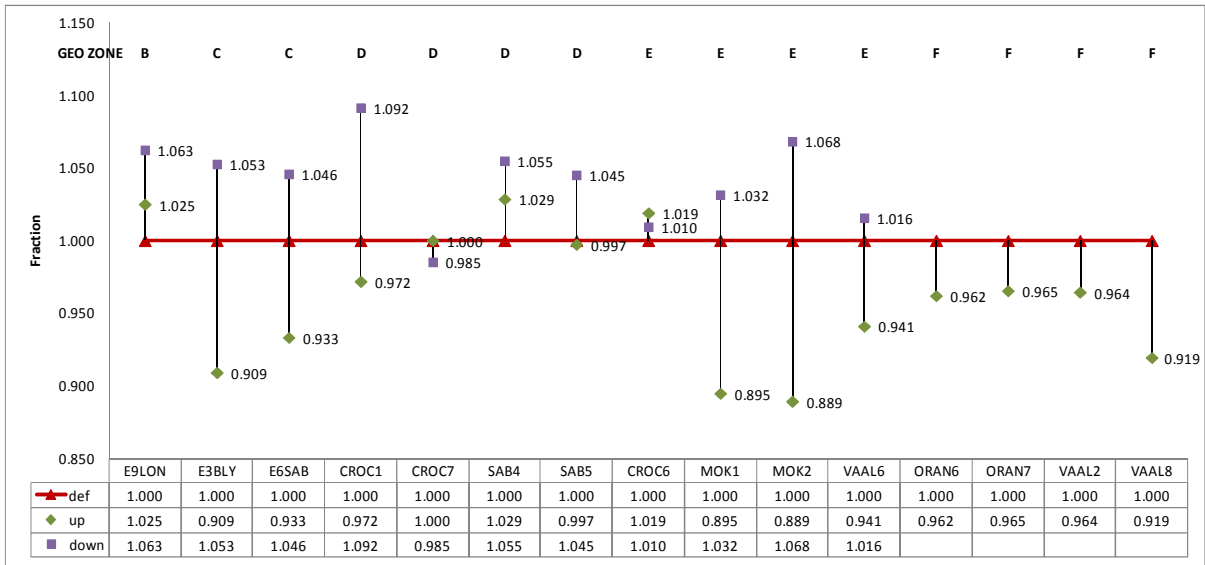
Site Name	Geo Zone	Fast Habitat Area – Workshop	Fast Habitat Area - Desktop	% Difference of Fast Habitat Area '-' indicates that the estimate is less	Workshop - REC	Total Flow Requirement - % MAR - WORKSHOP	Total Flow Requirement - % MAR - DESKTOP	% Difference of Total Flow Requirement '-' indicates that the estimate is less
CROC6 – Knongoma (Crocodile)	Higher – D		2198.21	55	B		42.9	-2
	Default – E	1415.56	1287.16	-9		43.9	42.1	-4
	Lower – F		1089.03	-23			42.5	-3
MOK1 – Vaalwater (Mokolo)	Higher – D		124.80	14	C/D		25.5	53
	Default – E	109.09	69.18	-37		16.7	28.5	71
	Lower – F		28.26	-74			29.4	76
MOK2 – Tobacco Farm (Mokolo)	Higher – D		515.44	57	B/C		27.3	38
	Default – E	327.49	349.50	7		19.8	30.7	55
	Lower – F		260.18	-21			32.8	66
VAAL6 – Klip (Vaal)	Higher – D		165.86	3	B/C		23.9	2
	Default – E	161.28	83.15	-48		23.4	25.4	9
	Lower – F		40.35	-75			25.8	10
ORAN6 – Caledon (Orange)	Higher – E		1190.24	-42	D		17.7	-12
	Default – F	2034.73	800.52	-61		20.1	18.4	-8
	-							
ORAN7 – Kraai (Orange)	Higher – E		424.68	-61	C		22.3	23
	Default – F	1087.81	274.85	-75		18.1	23.1	28
	-							
VAAL2 – Grootdraai (Vaal)	Higher – E		503.56	-40	C		21.7	71
	Default – F	834.20	376.79	-55		12.7	22.5	77
	-							
VAAL8 – Bavaria (Vaal)	Higher – E		614.40	-5	C		22.8	98
	Default – F	643.47	367.06	-43		11.5	24.8	116
	-							



**Figure 8-3 Comparisons of Workshop and Desktop Fast Habitat Areas Using different Geo Zones (def = default, up = higher & down = lower)**



**Figure 8-4 Recommended EWR Flow Requirements for Workshop and Desktop using Different Geo Zones (def = default, up = higher & down = lower)**



**Figure 8-5 Comparison of Desktop EWR Flow Requirement with Adjusted Geo Zones (def = default, up = higher & down = lower)**

**Table 8-8 Workshop and Desktop Comparisons – comparing the Rate of Change of Fast Habitats and EWR Flow Requirements**

Site Name	Geo Zone	Discharge (% of Baseflow)											% Difference of Total Flow Requirement ‘-’ indicates that the estimate is less	% Difference of Fast Habitat Area ‘-’ indicates that the estimate is less
		0	10	20	30	40	50	60	70	80	90	100		
		<b>Difference between Workshop and Desktop % Fast Habitat at Specific Percentages of Maximum Baseflow</b>												
<b>E9LON – Lone Creek River (Sapie)</b>	Higher	0	-47	-44	-37	-44	-54	-42	-48	-30	-31	0	1	138
	Default	0	-61	-72	-69	-66	-70	-30	-33	-15	-20	0	-2	129
	Lower	0	-7	-7	-14	-19	-35	-18	-30	-10	-18	0	5	41
<b>E3BLY – Blytaanspruit (Crocodile)</b>	Higher	0	-29	-79	-78	-68	-54	-33	-32	-13	-14	0	-24	94
	Default	0	-11	-33	-39	-32	-21	-11	-18	0	-10	0	-16	34
	Lower	0	4	-30	-37	-28	-12	-2	-12	5	-5	0	-12	10
<b>E6SAB – Sabaan (Sapie)</b>	Higher	0	-16	-2	5	5	8	18	9	9	5	0	108	5
	Default	0	-15	-8	1	7	10	14	3	3	3	0	123	20
	Lower	0	-33	-33	-14	-3	6	9	0	-11	-8	0	133	48
<b>CROC1 - Valyspruit (Crocodile)</b>	Higher	0	284	323	320	346	153	248	145	94	33	0	-11	19
	Default	0	289	326	324	348	152	247	146	93	33	0	-8	10
	Lower	0	330	356	353	380	176	262	160	102	42	0	0	-44
<b>CROC7 – Kaap (Crocodile)</b>	Higher	0	3	-6	-22	-4	3	3	-3	-2	0	0	30	0
	Default	0	11	-6	-16	0	8	8	8	1	2	0	30	-3
	Lower	0	35	8	-6	9	16	14	3	4	3	0	28	-23
<b>SAB4 – Mac Mac (Sapie_Sand)</b>	Higher	0	-16	-40	-29	-24	-28	-27	-26	-13	-4	0	27	77
	Default	0	0	-3	-22	-24	-26	-16	-12	-9	-4	0	23	86
	Lower	0	0	6	-1	-10	-17	-14	-12	-9	-2	0	30	25

<b>SAB5 – Marite (Sapie_Sand)</b>	Higher	0	-26	-42	-34	-22	-16	-11	-2	-2	1	0	4	38
	Default	0	-27	-28	-17	-3	1	-4	-2	-1	2	0	4	35
	Lower	0	0	-8	-3	-1	-2	-7	1	0	3	0	9	-4
<b>CROC6 – Knongoma (Crocodile)</b>	Higher	0	-43	-43	-32	-24	-21	-21	-13	-7	-4	0	-2	55
	Default	0	-12	-9	-12	-7	-8	-10	-7	-5	-6	0	-4	-9
	Lower	0	-5	-1	0	-4	-3	-6	-2	-2	-3	0	-3	-23
<b>MOK1 – Vaalwater (Mokolo)</b>	Higher	0	-9	-2	4	11	14	15	19	-1	0	0	53	14
	Default	0	18	21	17	19	24	21	22	10	6	0	71	-37
	Lower	0	22	34	34	42	45	39	40	22	12	0	76	-74
<b>MOK2 – Tobacco Farm (Mokolo)</b>	Higher	0	-32	-29	-19	-15	-12	-6	-2	-2	-1	0	38	57
	Default	0	-3	0	-2	-7	-4	-7	-2	-4	-2	0	55	7
	Lower	0	4	13	10	4	6	1	2	3	2	0	66	-21
<b>VAAL6 – Klip (Vaal)</b>	Higher	0	-17	-21	-17	-21	-18	-13	-7	-3	-3	0	2	3
	Default	0	1	18	23	18	9	6	6	-2	-2	0	9	-48
	Lower	0	0	22	35	32	34	33	22	15	7	0	10	-75
<b>ORAN6 – Caledon (Orange)</b>	Higher	0	17	14	18	18	16	9	1	0	0	0	-12	-42
	Default	0	24	28	32	25	18	11	3	0	-1	0	-8	-61
	Lower													
<b>ORAN7 – Kraai (Orange)</b>	Higher	0	20	31	18	6	9	16	15	9	6	0	23	-61
	Default	0	25	44	35	26	21	21	24	16	6	0	28	-75
	Lower													
<b>VAAL2 – Grootdraai (Vaal)</b>	Higher	0	37	37	26	30	29	26	18	15	9	0	71	-40
	Default	0	44	49	33	33	30	27	23	15	12	0	77	-55
	Lower													
<b>VAAL8 – Bavaria (Vaal)</b>	Higher	0	11	12	7	10	0	-12	-1	-3	0	0	98	-5
	Default	0	20	25	20	20	7	-6	1	1	3	0	116	-43
	Lower													

## 8.5 Discussion of Workshop and Desktop Comparisons

Prior to the detailed site specific evaluations two general observations could be made for all 15 sites:

- The abundance of fast habitat decreases as the Geo Zone changes from A to F and this is largely due to the increase in channel width and bed width (Table 8-7 and plots in Appendix B).
- The EWR requirements are relatively insensitive to changes in Geo Zone (Figure 8-5).

Sites E9LON, E3BLY and E6SAB all represent relatively small headwater catchments where there is a potential for some of the uncertainties to be quite large. With respect to Geo Zone, such headwater catchments might be expected to fall into categories A to C and have relatively steep channel slopes. For all three sites the measured valley slope suggests a Geo Zone that is one lower than the default zone obtained from the geomorphological database. The results suggest that the use of a lower Geo Zone will provide a better match between the W and D habitats for E9LON and E3BLY. However, even using a lower Geo Zone, the desktop FC frequency results for E9LON remain very different to the workshop. The comparison plots of the cross-section clearly suggest that the main difference is associated with a much narrower channel estimated by the desktop method. A comparison of the estimated channel forming discharge ( $6.5 \text{ m}^3 \text{ s}^{-1}$ ) with standard design flood estimation methods used for small catchments in South Africa (Alexander, 1990) suggests that the estimate is too low and that the discharge should be in the range of 12 to  $20 \text{ m}^3 \text{ s}^{-1}$ . Increasing this discharge to between 12 and  $20 \text{ m}^3 \text{ s}^{-1}$  increases the channel width to between 9 and 11m, a far better match to the shape of the surveyed cross-section and, inevitably, a reduction in fast habitats so that the desktop FC frequency results are closer to the workshop outputs. There is an indication that the channel forming discharge estimates for E3BLY and E6SAB are also under-estimated, but not to the same degree. Small increases in the estimated channel widths for these two sites also result in improved matches to the workshop hydraulic results.

The results tables and diagrams suggest that the EWR results for these three sites are not very sensitive to changes in the Geo Zone and the same degree of insensitivity applies to changes in the channel forming discharge and therefore channel width. The desktop EWR results for sites E9LON and E3BLY are close to the workshop results, while the workshop results for site E6SAB (21.5% nMAR) were clearly affected by the very low flows that are evident in the simulations of the present day hydrological regime and cannot really be compared to the desktop outputs. This is confirmed when the REC is aligned to the present day flows in the ecological sub-model (Chapter 3), the resulting EWR after aligning is 22.2% nMAR. Tests of changes to the % point on the baseflow duration curve suggested that EWR results are relatively insensitive to uncertainties in this parameter.

Site CROC1 has no Geo Zone-slope incompatibility and there are small differences between the W and default D FC habitat areas (Table 8-7). However, the FC rate of change plots show extremely large differences which are accounted for by the highly incised observed cross-section. This site was unable to provide any indication of the validity of the hydraulic sub-model estimations due to the distinctive cross-sectional profile. Nevertheless, the EWR requirements are insensitive to the differences in FC estimation for all Geo Zone simulations, thus suggesting that the hydrological regime is the critical issue at this site.

Site CROC 7 has no Geo Zone-slope incompatibility and there are small differences between the W and D FC habitat areas. Furthermore, the FC rate of change and estimated cross-sectional profiles for the default Geo Zone are very similar to the workshop results which indicates that the hydraulics for this site represent the region well. The desktop EWR results are 30% higher than estimated during the workshop.

Site SAB4 has no Geo Zone-slope incompatibility but the valley slope lies very close to the border between Geo Zones C and D. Both Geo Zone C and D estimate more fast habitats than for the observed cross-section. The estimated cross-sectional profiles for Geo Zones C and D indicate that the channel widths are under-estimated and changing to Geo Zone E (thereby increasing the width) results in a better representation of fast habitats and FC rate of change (Table 8-7). A similar increased width could be generated in the model by

increasing the channel forming discharge (the default estimate is  $27.2 \text{ m}^3 \text{ s}^{-1}$ ). The Mkhundi and Kachroo (1997) flood region (4) covers a very topographically diverse region and this site is part of an escarpment catchment where flood peaks in relation to catchment area might be expected to be higher than for less steep catchments elsewhere in the region. The macro roughness of the observed cross-section is approximately double the value of the model estimated macro roughness and this will have a large impact on the FC rate of change. It is possible (but difficult to confirm without further detailed field surveys) that the site used in the workshop is not very representative of the local channel characteristics, but was selected for its ecological sensitivity. It is also possible that a different maximum baseflow was used in the workshop and the sensitivity of the desktop results to a change in the % point of the baseflow flow duration curve was assessed for both this site and the previous one (CROC7). Adjusting the % baseflow in the hydrological sub-model from 20% to 40% reduced the wet season maximum baseflow discharge from  $4.7 \text{ m}^3 \text{ s}^{-1}$  to  $3.48 \text{ m}^3 \text{ s}^{-1}$  and an EWR result of 45.7% nMAR (i.e. only a small change – see Table 8-7). For SAB4, the wet season baseflow discharge decreased from  $1.9 \text{ m}^3 \text{ s}^{-1}$  to  $1.4 \text{ m}^3 \text{ s}^{-1}$  but the EWR result remained at 45% nMAR. Aligning the CROC7 EWR B category requirements in the ecological sub-model to the present day condition generates an EWR result (35.8% nMAR) that is much closer to the workshop results. For SAB4, using the present day alignment option did not have much effect as the present day and natural hydrological regimes are very similar.

Site SAB5 has no Geo Zone-slope incompatibility and the difference between the W and D FCs is largely associated with the observed multi-thread cross-section. Nevertheless, the desktop EWR results are very similar to the workshop results even though multi-thread channels have not been considered in the estimation of the hydraulic cross-section. The lower Geo Zone (E) represents the total fast habitat area and the FC rate of change very well despite the fact that the two cross-sections are very different. This illustrates that it may not always be necessary for the desktop model to accurately represent the observed cross-section to be able to accurately represent the hydraulic characteristics. However, there are extreme cases where differences in W and D cross-sections will result in very different hydraulic characteristics (see CROC1 site discussed above).

Site CROC6 has no Geo Zone-slope incompatibility but it could be a Geo Zone F due to the valley slope being close to the range limits. Both Geo Zone E and F estimate less total fast habitat than the workshop with the default Geo Zone being better, while the F Geo Zone gives a better representation of the FC rate of change. The conclusion is that the hydraulic characteristics are well represented and the W and D EWR results are also very close.

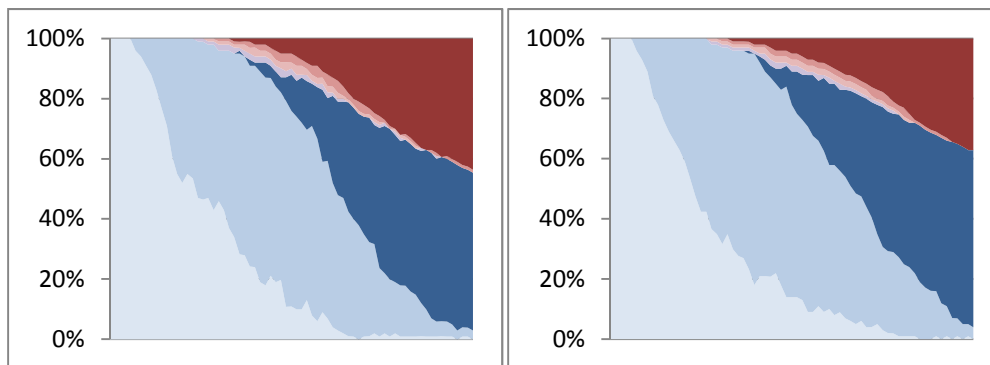
Site MOK1 has no Geo Zone-slope incompatibility but it could be a Geo Zone D due to the valley slope being close to slope limit between zones D and E. Geo Zone D estimates more fast habitat and Geo Zone E estimate less fast habitat, compared to the observed, with the Geo Zone D habitat areas being closer to the W value. The FC results are assessed to be adequate given the complexity of the observed channel profile.

Site MOK2 has no Geo Zone-slope incompatibility and the estimated FC habitat areas and the simulated FC rate of change for the default and lower Geo Zones are satisfactory when compared to the W results. The higher Geo Zone poorly represents the hydraulic conditions because of the much lower estimated channel width. The desktop EWR estimates for MOK1 and MOK2 are both substantially higher than the workshop results. Aligning the desktop EWR to the present day condition improved the estimates by a small amount, but the desktop EWRs remain higher than the workshop. The likely reason for this is that there was some question about the validity of the present day hydrological simulations during the workshop (the participants believed the impacts of upstream irrigation to be greater than simulated) and this affected the way in which the flow requirements were determined (DWA, 2010c).

Site VAAL6 has no Geo Zone-slope incompatibility and the default and lower Geo Zones significantly under-estimate the FC habitats, whereas the higher Geo Zone estimate is much closer. The EWRs for all simulations compare very well with the workshop EWR result.

Site ORAN6 has no Geo Zone-slope incompatibility and the total fast habitats for both Geo Zones E and F are substantially under-estimated. The reason for this is that the estimated channel widths are over-estimates and therefore the estimated channel forming discharge

was investigated further. Using a nearby flow gauge, the mean annual flood discharge was estimated to be in the region of around  $800-900 \text{ m}^3 \text{ s}^{-1}$  and not the  $1518 \text{ m}^3 \text{ s}^{-1}$  given by the Mkhandi and Kachroo (1997) approach. The RDRM and HABFLO simulations were repeated with an estimated channel forming discharge of  $880 \text{ m}^3 \text{ s}^{-1}$  and the revised FC class distributions are illustrated in Figure 8-6. The improvement in the representation of the habitat is very clear while the EWR results, which were already adequate, are even closer to the workshop EWR.



**Figure 8-6 FC Area Plots of ORAN6 –LEFT side: revised desktop results; RIGHT side: the workshop results**

The most obvious point about Site ORAN7 is the complete miss-match between the workshop and desktop channel cross-section sizes. The observed cross-section would appear to be very small for the catchment size and the discharges that would be expected. It is therefore concluded that the entire cross-section was not been included in the survey and that further assessments for this site would need more details for the observed cross-section.

Site VAAL2 has no Geo Zone-slope incompatibility but it could be a Geo Zone E due to the valley slope being close to the limits between E and F zones. The fast habitats are underestimated due to the wide channels that are estimated by the desktop model, compared to the relatively confined observed channel. VAAL2 is a site below the Grootdraai dam and thus the confined channel may be a result of possible effects on channel morphology due to prolonged medium flow releases for irrigation (Brandt, 2000).

Site VAAL8 has no Geo Zone-slope incompatibility and the default estimated FCs are significantly under-estimated whereas the higher Geo Zone estimates the FCs very well

suggesting either a mismatch in the Geo Zone or that the channel forming discharge could be over-estimated resulting in a wider channel. There is not enough reliable information available to assess the validity of the channel forming discharge estimate (i.e. no stream flow gauging sites in the vicinity of the site).

The desktop EWR results for VAAL2 and VAAL8 are poor in comparison to the workshop results (approximately double). The reason for this is that the workshop EWR requirements for both VAAL2 and VAAL8 are very low for what is typically expected for a C category river in this climate region and suggests that the impacts of allowing for present day flow conditions in the workshop might be the issue. However, aligning the RDRM to the present day conditions did not substantially affect the desktop results and additional factors may have influenced the workshop results.

## **8.6 Conclusions**

It was not the original intention of the assessment to consider the modifications that can be made to the RDRM results by making use of the present day flow regime characteristics (Chapter 3). However, many of the EWR workshop results are influenced by this information and therefore any final comparison between the workshop and desktop results cannot realistically ignore the fact that the present day flows may not only affect the ecological protection category, but also the flows required to meet that category. There are certainly sites where aligning the desktop results to the present day situation (as represented by the simulations of the present day flows) improved the match between the EWR results for the workshop and desktop estimates. However, there are also others where the use of the alignment option did not improve the situation. It has to be recognised that within detailed EWR workshops, the group of specialists frequently use site specific information in the way in which they interpret the hydrological and hydraulic data. It is not always possible to access this information, nor the way it was used to influence the EWR determination, from the workshop reports. At the same time, it is not expected that a desktop type of determination method would account for this type of information.

At the start of this section it was noted that the EWR results are relatively insensitive to changes in the Geo Zone, this insensitivity is apparent for most of the other input

parameters of the hydraulic sub-model. The conclusion is that the final EWR results are not very useful for evaluating the applicability of the structure and parameters of the hydraulic sub-model. The evaluations suggest that it is necessary to compare the details of the hydraulic sub-model output with field surveyed hydraulic characteristics to adequately assess applicability. However, this chapter has also revealed that care must be exercised in the interpretation of such comparisons. One of the issues is related to the selection of ecologically 'critical' channel cross-sections for Rapid III, Intermediate or Comprehensive ER, while the desktop model attempts to generate 'representative' cross-sections and hydraulic conditions. Consequently, without further details being provided about the field site selection process, it is very difficult to assess how much difference there is likely to be between the 'critical' field site and other cross-sections within the same channel reach. It is therefore sometimes difficult to assess the extent to which a workshop cross-section can be used to evaluate the outputs from the hydraulic sub-model. The CROC1 site provides the best example of this issue.

In some cases improvements in the simulations of the hydraulic characteristics were obtained through adjustments to the channel forming discharge. There are very few stream flow gauging stations on small catchments (less than approximately 100 km<sup>2</sup>) in South Africa and therefore they would have been under-represented in the Mkhandi and Kachroo (1997) study. It is inevitable that there will be substantial uncertainty in the estimates of channel forming discharge for small catchments. Regionalised estimates for very large catchments that cross flood regions are also expected to be uncertain.

The approach used for estimating the maximum channel width is based on discrete parameter values for each Geo Zone and the hydraulic results are frequently sensitive to the selection of the zone. Several sites in Table 8-6 have valley slopes that fall close to the boundary between two Geo Zones and therefore selecting one or the other can have a large impact on the hydraulic results. The conclusion is that an improvement to the hydraulic sub-model could be made by introducing continuous functions for estimating the parameters in the maximum width estimation equation based on the valley slope, rather than discrete parameter values based on Geo Zone (which in turn are defined by valley slope).

## 9 CONCLUSIONS AND RECOMMENDATIONS

Rivers are life-sustaining systems that are important to mankind and the aquatic ecosystem. However, the natural services provided by river ecosystems are threatened and many countries have recognised the need to protect their water resources from misuse and poor management. They have begun implementing policies to conserve riverine biodiversity, improve ecosystem health and/or restore the ecosystem integrity. This has led to the determination of Environmental Flows (EF) which is the design of a flow regime to maintain a river in some agreed ecological condition and is seen as a compromise between river basin development and maintenance of the river ecology (Smakhtin, 2007).

South Africa began to address the problem in the 1980s and in 1998 enacted the South African National Water Act. The NWA stipulates that future water resources developments should be environmentally sustainable and that a component of the natural flow of rivers should be reserved to ensure some level of ecological functioning (Hughes and Hannart, 2003). The water required to protect aquatic ecosystems of the water resource is referred to in the NWA as the Ecological Reserve (ER). The determination of ERs may be undertaken at several levels of confidence with the desktop study being the lowest level. Desktop studies are a rapid, low confidence method of assessment that is used to obtain quick, initial estimates of EFs. The Desktop Reserve Model (DRM, Hughes and Münster, 2000; Hughes and Hannart, 2003) was developed to generate desktop EF estimates for rivers in SA.

The development of the DRM was completed at a time when there was no widespread database on the ecological functioning of South African rivers. The DRM model was developed using the results from past EWR studies and based the flow recommendations associated with different ecological river conditions on hydrological characteristics and specifically on the variability of the natural flow regime. Therefore the DRM is very dependent upon the characteristics of the reference (generally naturalised) hydrology used and geomorphological, hydraulic and ecological (flow-hydraulic-habitat-ecological) relationships were implicitly incorporated along with any inconsistencies in the results that were an inevitable consequence of the developing methods of ER determination.

Data collection and developments in the scientific disciplines related to EF studies over the past few years prompted a review and update of the DRM. The objective of the Revised Desktop Reserve Model (RDRM) is to incorporate flow-hydraulic-habitat-ecological relationships through the design and development of hydrological, hydraulic and ecological sub-models. The development of these sub-models was expected to draw on the experience of past EWR studies and contribute to improved confidence in the results of rapid desktop assessments undertaken by less experienced individuals. The research presented in this thesis is a direct contribution to the development of the hydraulic sub-model and the objective was to develop a hydraulic sub-model that is appropriate for inclusion in the integrated RDRM and that will provide the essential links between the ecological sub-model and the hydrological sub-model.

Three design principles of the hydraulic sub-model were established; (i) the model should operate in a desktop environment without the support of field data and experienced individuals, (ii) the model should produce realistic hydraulic conditions for any part in SA through hydraulic habitat modelling procedures, within a “reasonable” degree of certainty, using hydraulic parameters and characteristics estimated from readily available information, (iii) the development of the model should be guided by the recent developments in the science and practice of ER determination within a South African context.

Literature reviews of several topics were undertaken to establish the various methods of EF assessments used, the role of hydraulics within these methods and the role of hydraulics in SA EWR. Ecohydraulic modelling within SA was also reviewed to establish the input, output and parameter requirements for the models. The literature reviews informed the importance of hydraulic analysis in holistic EF assessment methods in that it is a crucial link between ecology and hydrology. Furthermore, reviews of previously developed hydraulic estimation equations were undertaken because no field data are expected to be available for the desktop hydraulic sub-model. While the direct use of the relationships was limited, the forms of the relationships were used as a guide in the estimation and development of the hydraulic sub-model parameters.

Ecohydraulic results in SA relate discharge to ecologically relevant hydraulic parameters as well as the relative spatial composition of hydraulic habitat conditions. The fundamental relationships required to produce these results were identified and the important parameters within these relationships were estimated using data from the hydraulic database of past EWR studies (Birkhead and Desai, in press). An estimation program was developed to facilitate the processing of the large amount of data and generated values for the parameters identified. The estimation program entailed the importing of observed cross-sectional profiles and rating curves. The parameters were thereafter computed based upon the specification of a maximum flow depth, gradient at bankfull and Manning's roughness coefficients with related flow depths for 300 cross-sections. The parameter optimisation was based on maximising the coefficient of efficiency (Nash and Sutcliffe, 1970) statistic for observed and estimated depth-wetted area relationships and rating curves.

The hydraulic estimation relationships were subsequently developed through standard multiple regression procedures using the estimated parameter values, readily available information and guided by equation forms (i.e. power and linear functions) that have been used in previous studies and are documented in the literature. The relationships developed were moderately to poorly correlated and this was attributed to, (i) the various uncertainties associated with developing relationships for complex models, i.e. the right answer (a realistic rating curve shape, for example) can be obtained for the wrong reasons and (ii) the inherent flaws and limitations in the estimation program related to interactions between the parameter values. It was concluded that the regression relationships developed could not be used directly to accurately represent the hydraulic characteristics for the RDRM because of the limitations and potential errors associated with the use of the estimation program, as well as the complex interaction of the parameters. An alternative, rule-based approach was adopted to develop relationships that are realistic and based on physical characteristics, technical theory and various assumptions using past experience (parameter ranges, field data and results) and literature (equation forms) and partly guided by the estimation and regression results. The development of the relationships required an iterative process of testing and application.

Several attempts to validate the relationships developed proved to be unsuccessful because of the complex interaction between the parameters and thus an assessment of the overall output of the hydraulic sub-model was used to assess the validity of this complex model. The hydraulic sub-model was integrated into the RDRM and the hydraulic conditions as well as the overall desktop EWR requirements were computed for several past EWR sites. The estimated hydraulic results were used as inputs into the South African ecohydraulic model (HABFLO) to determine the hydraulic habitat characteristics based on the changes in frequency of critical fast habitats with changes in discharge. The estimated hydraulic habitats were compared to the hydraulic habitats computed in past EWR studies using field surveyed channel cross-sections. The hydraulic habitat comparisons revealed that the hydraulic sub-model is generally capable of reproducing representative hydraulic conditions. These assessments were very useful in identifying which parameters of the hydraulic sub-model are most sensitive and which are potentially subject to the most uncertainty given the available information that can be used to estimate their values.

While the model has been quite extensively tested across a range of different sites (with respect to catchment size, climatic characteristics, etc.), it has been developed to produce characteristic regionalised hydraulic conditions relevant to estimating desktop ERs and is not intended for site specific modelling. During the analysis of the hydraulic sub-model it has already been noticed that there are some parts of the model that need to be refined to account for special cases. The following should be considered for future refinements of the hydraulic sub-model:

- Additional site data should be sourced so that further testing of the RDRM can be undertaken. The RDRM can be run for a random number of sites in the different regions of South Africa and the outputs can be compared to the data collected and the results of the modelling at these locations. The sites can also serve as additional data for revising the hydraulic estimation relationship.
- The Mkhundi and Kachroo (1997) flood region equations do not always estimate an appropriate value for the mean annual flood (particularly in small and very large catchments) and therefore the channel forming discharge is inadequately estimated. The channel forming discharge has a large influence on the size and shape of the

channel cross-section and therefore the hydraulic conditions. It is possible that the user will have access to information that allows the estimated values to be checked and refined (e.g. a nearby stream flow gauging station with accurate flood discharge records). It is therefore recommended that an improved method of estimating the mean annual flood should be investigated and that, in the meantime, users should be aware of the potential uncertainties in the estimate of the mean annual flood and check the values where possible. One of the identified problems with the structure of the hydraulic sub-model is the use of discrete parameters for each Geo Zone in the equation used to estimate maximum channel width. This problem manifests itself when a measured valley slope falls close to the boundary between two Geo Zones. Chapter 8 recommends that these discrete parameters should be replaced with continuous functions based on the valley slope. This change would reduce the sensitivity of the model to the selection of an appropriate Geo Zone. Part of the motivation for this recommendation is that the Geo Zones are currently defined only by the valley slope. A possibility exists that the geomorphic provinces developed by Partridge *et al.* (2010) could be used to categorise the hydraulic parameters but this would require additional site specific data to be obtained from each of the geomorphic provinces.

- An alternative to checking the validity of the channel forming discharge estimate is to use any available satellite (Google Earth, for example) or aerial photograph imagery to check the maximum channel width estimate. The imagery should be of a scale and resolution that is appropriate to the size of the channel. This approach was applied to the two sites where the channel forming discharge was thought to be poorly estimated (E9LON and ORAN6) and which have very different channel sizes. Despite the small size of the channel at E9LON, the channel width measured using Google Earth is close to the observed (Appendix B). Applying the approach to the ORAN6 site is much easier because of the wider channel and the Google Earth measurement also closely conforms to the field surveyed channel width. It is noted however that the use of Google Earth to replace the maximum width relationships is not envisaged as the use of Google Earth will also be subject to its own uncertainties; clear elevation data may not be available, subjective selection of a width by the user.

- Comparisons of the desktop and workshop channel cross-sections suggest that the hydraulic model tends to produce 'simpler' cross-sections than occur in reality and this is related to the way in which the basic channel shape is defined, as well as the use of the macro roughness parameter. While it is recommended that these approaches should be re-visited, it should be acknowledged that adding more 'reality' to the desktop generated cross-sections will always be difficult without including more site specific information as input to the model.

One of the sites used for the hydraulic sub-model assessment (VAAL2) is located below a major dam that is used for irrigation releases. It was speculated that the characteristics of this channel could have been altered by alterations to the flow regime of the river, a topic that has been discussed widely in the geomorphological literature (e.g. Brandt, 2000). It would be extremely useful therefore to investigate the possibilities of changing some of the hydraulic sub-model parameters to account for changes in the geomorphology of a river associated with upstream impacts on the flow and sediment regimes. While this type of investigation was beyond the scope of this study, the incorporation of a feedback loop from hydrological change to channel shape and size change would have great potential for assessing future catchment and water management scenarios. These effects are rarely, if ever, considered in most EWR studies, while channel changes can have large impacts on available habitat and could affect the volumes of water required to maintain ecological functioning.

Regionalised sediment information has not been taken into account during the development of the hydraulic sub-model because insufficient data were available to develop regional relationships for SA. However, it may be required when macroinvertebrates are included in the ecological sub-model. This is because the hydraulic variables typically used to specify macroinvertebrates flow classes are depth-averaged velocity, depth and substrate. Furthermore, sediment changes can profoundly affect the hydraulic characteristics within a river system (see previous point) and specifically the channel shape (e.g. a dam may trap sediment and release clear water which may result in downstream channel instability because the channel and banks begin to erode to satisfy the sediment carrying capacity of the flow, Collier *et al.*, 1996). If these changes can be quantified, the

algorithm to compute the channel cross-sectional profile (i.e. shape, macro and micro roughness) could be refined.

It can therefore be concluded that further developments of the hydraulic sub-model would benefit from a comprehensive review of previous studies and the literature on the modification of channel form consequent on changes to flow and sediment regimes. Developing the model to account for the effects of flow and sediment regime changes would require a sound understanding of the effects of changes in flow magnitude and frequency characteristics on channel size and shape, as well as substrate structure. The current version of the model uses only an estimate of channel forming discharge to estimate the maximum channel width and depth, while a future version could include more details of the magnitude-frequency characteristics of the flow regime (both natural and modified) to quantify the channel cross-section characteristics. If such a development were possible, given the constraints of scientific understanding and the availability of data to parameterise the model, it would allow the model to be used to assess EWR scenarios not only in terms of the ecological impacts, but also in terms of the effects on channel geomorphological characteristics (size, shape, substrate, etc.).

While the hydraulic sub-model has been specifically developed for application in SA, the parameter estimation routines used for the hydraulics sub-model have been based on approaches used in many countries. There is therefore a potential for the model to be applicable in other countries as long as there exist data that can be used to either check the applicability of the South African specific relationships, or develop alternatives. Certainly the flood regions are specific to South Africa and a new set of regions and equations would be needed for other countries e.g. Alpine river systems are fed by glacial icemelt, snowmelt and groundwater (Brown *et al.*, 2003) while South African rivers systems are fed by rainfall and runoff and are mostly located in semi-arid areas. The use of the Geo Zones are also quite specific to SA and are unlikely to be applicable to a wide range of other countries and alternative river classifications may need to be used.

The testing and analysis that has been carried out suggests that the hydraulic sub-model has reached a stage where it can satisfactorily be incorporated in the RDRM and that it is

adequately robust in most situations. It should not be assumed that it will generate results that are the same as site specific intermediate or comprehensive ER studies; 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 main observations that arose out of the assessment of the hydraulic sub-model is that while the simulated hydraulic habitat characteristics are sensitive to changes in the hydraulic parameter values, the estimated EWRs are generally quite insensitive. The implication is that the hydrological characteristics are the main driving force, but this is consistent with observations from detailed EWR workshops. This does not imply that the hydraulic sub-model is of no value as it may be used to identify uncertainties in the hydrological data used as part of the input to the integrated RDRM. It has been noted during some previous EWR determinations that where there are possible problems with simulated hydrological time series these are identified at workshops by noting inconsistencies in the expected (by the ecological specialists) habitat variability characteristics and those suggested by the simulated flows linked with the field derived hydraulics. The inclusion of the hydraulic sub-model as part of the RDRM allows these potential inconsistencies to be identified within a desktop modelling approach.

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# APPENDIX A

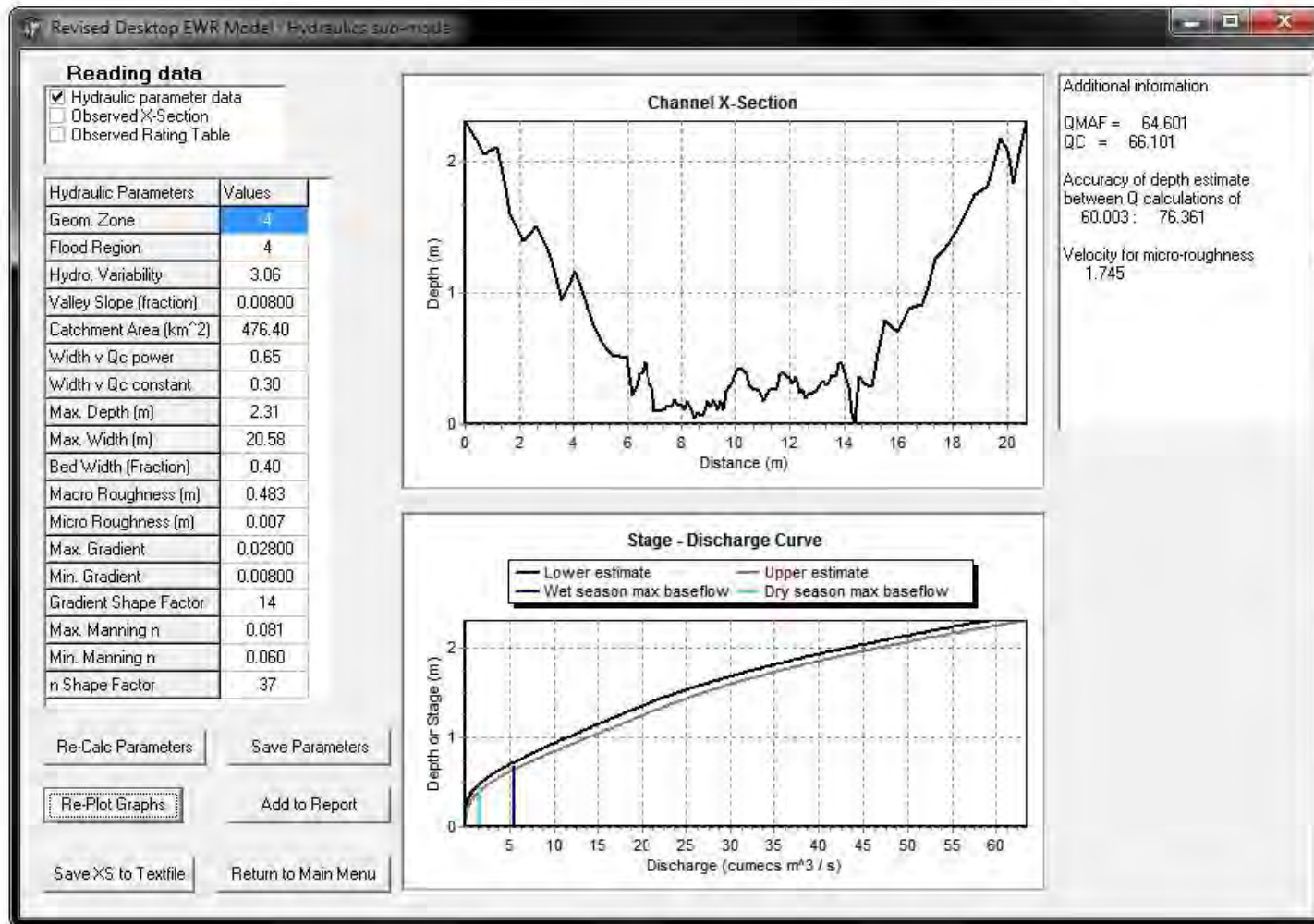


Figure A-1    Hydraulic Estimation for EWR Sabie 5

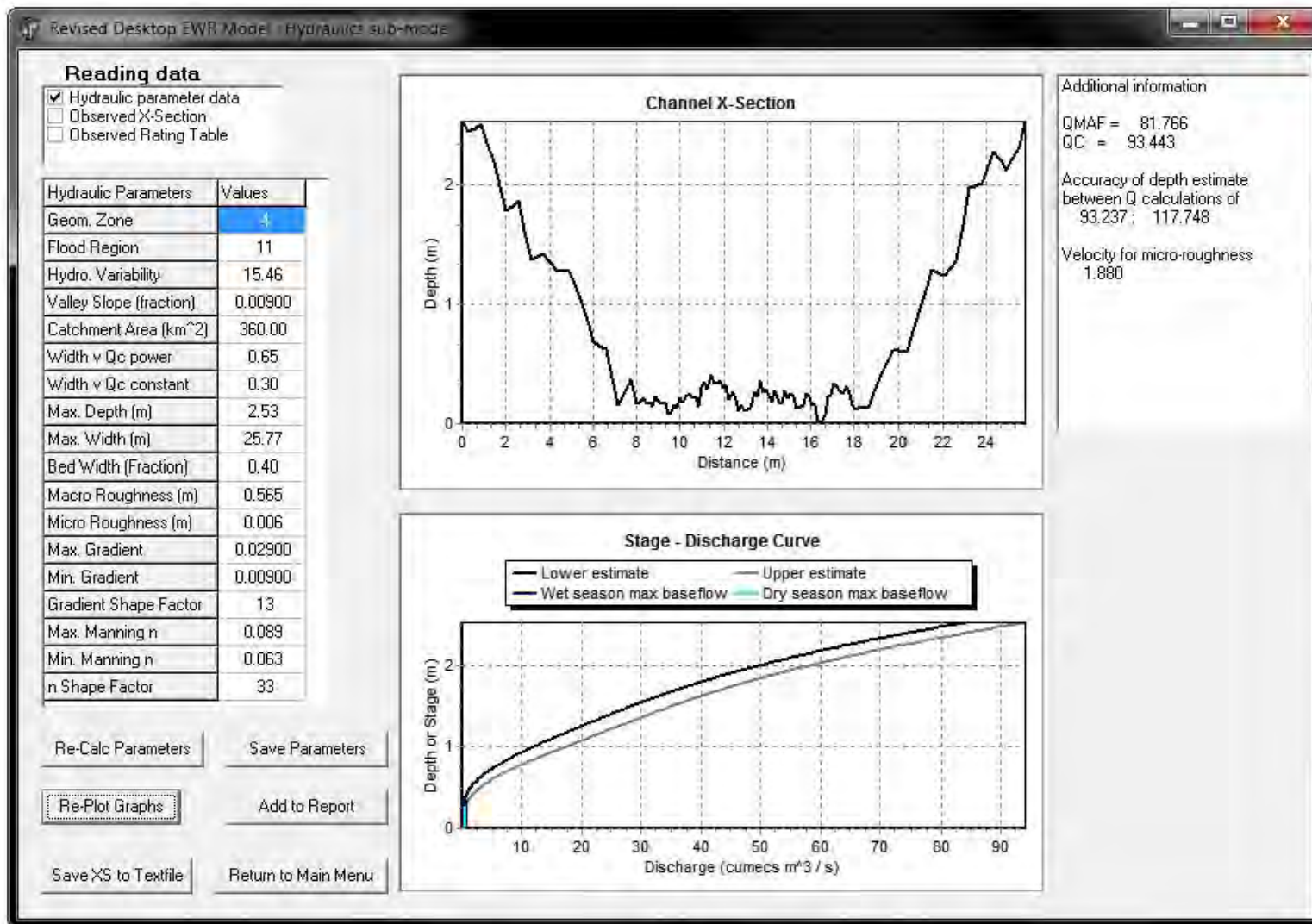


Figure A-2 Hydraulic Estimation for EWR Kromme 1

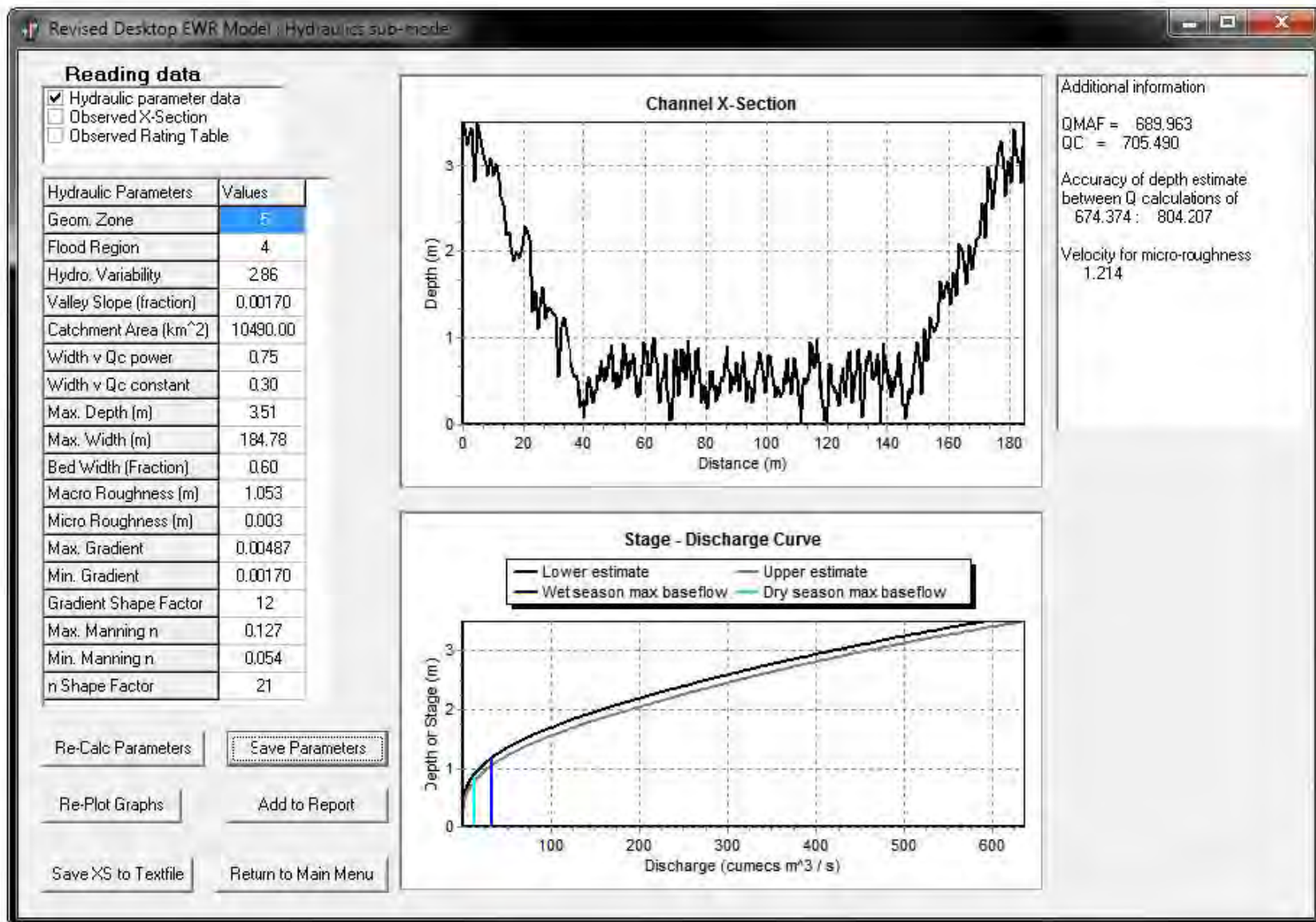


Figure A-3 Hydraulic Estimation for EWR Crocodile 6

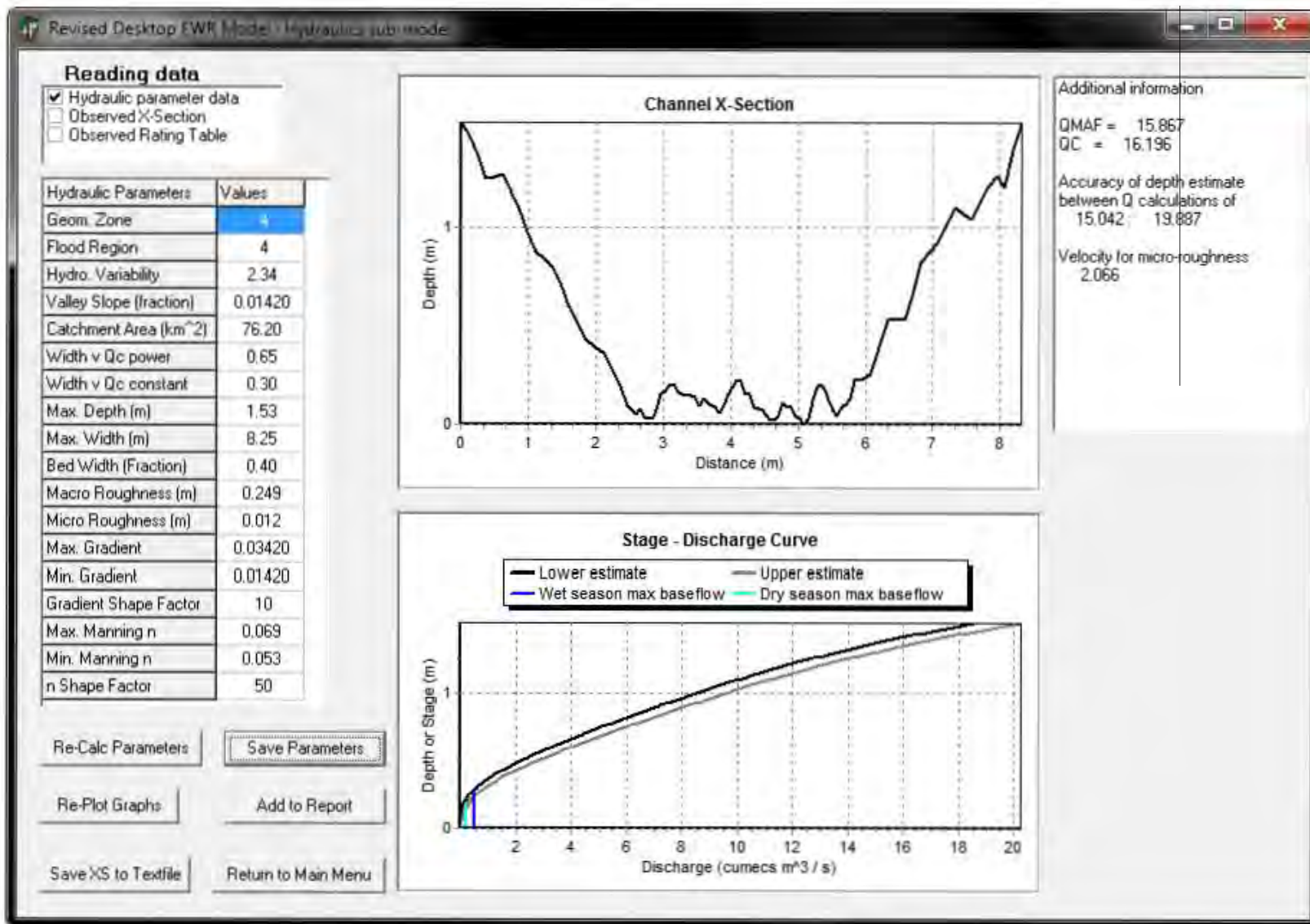
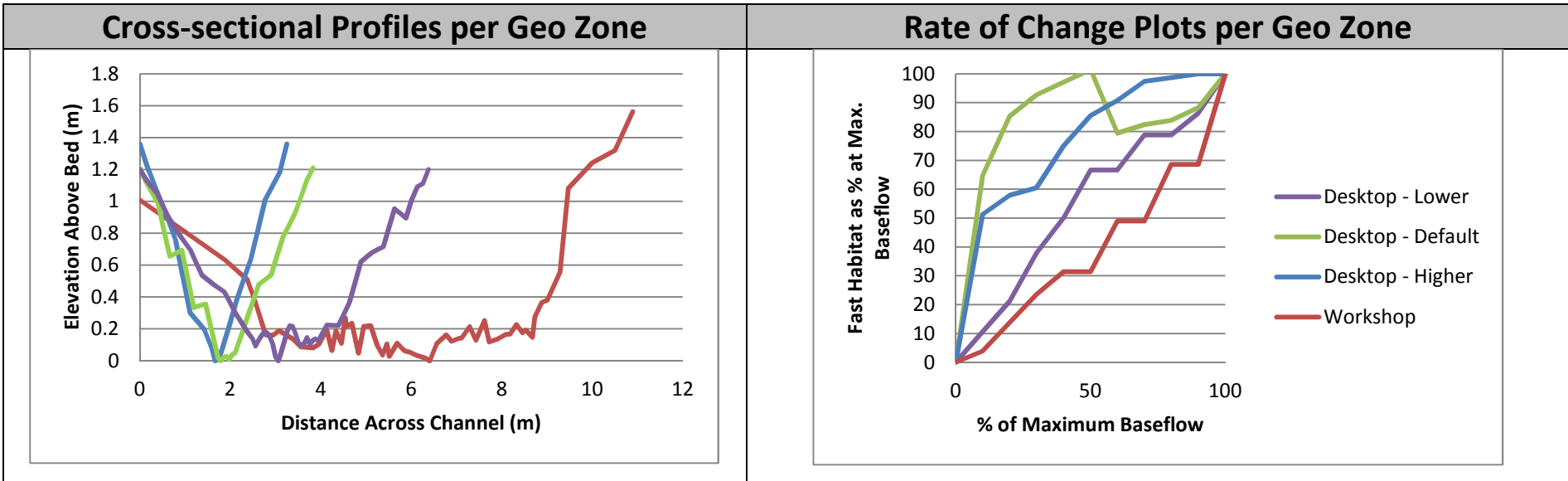
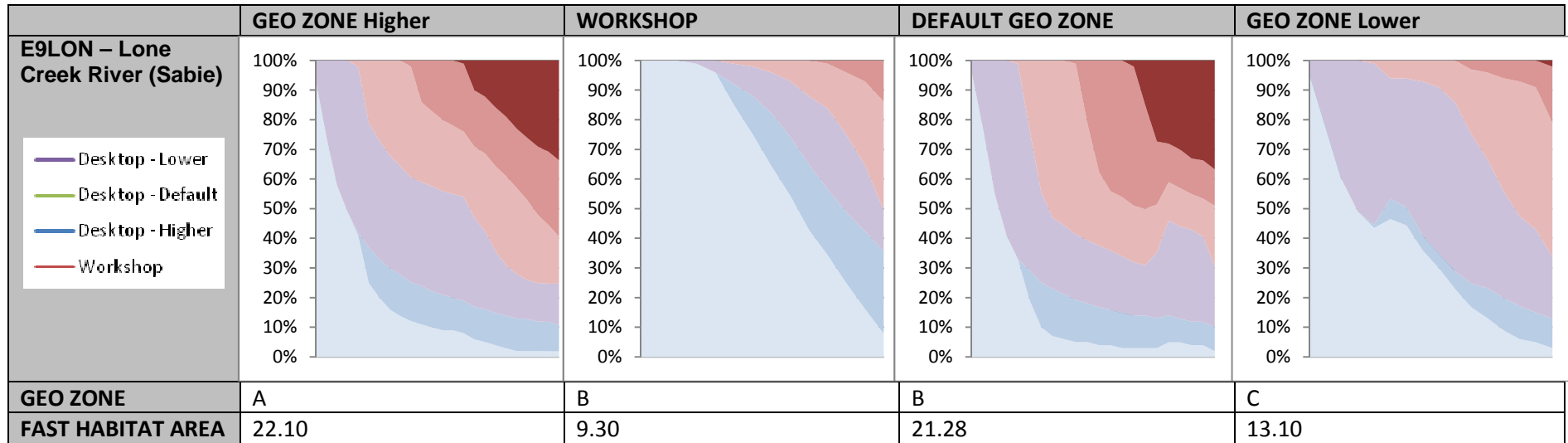

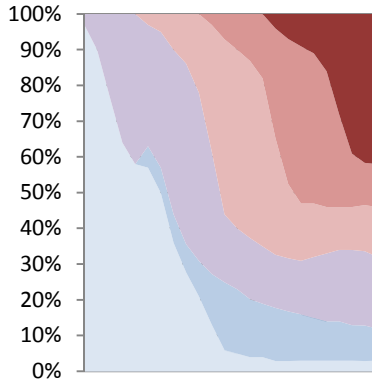
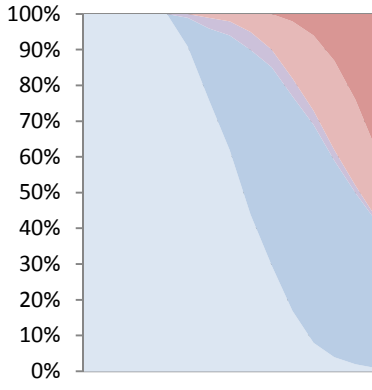
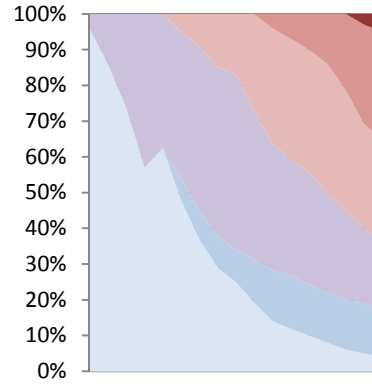
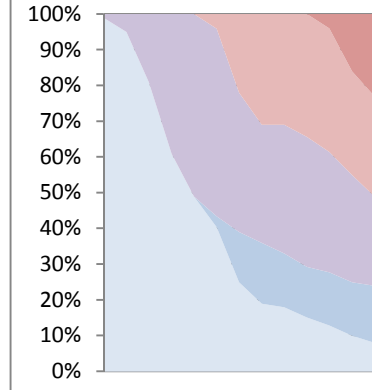
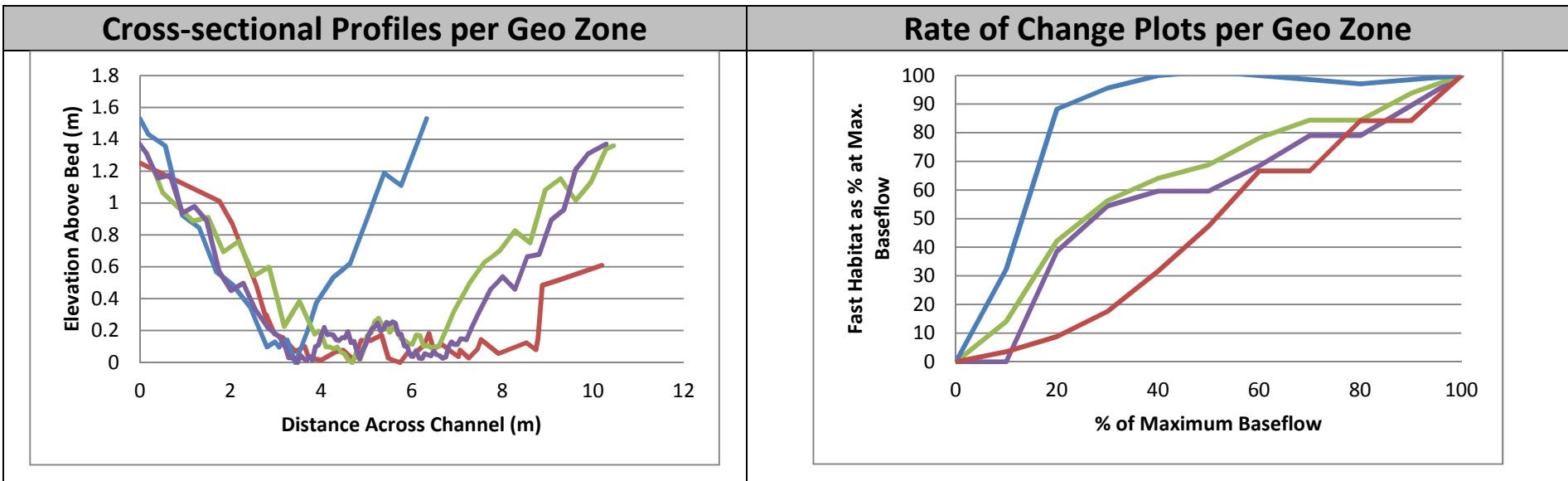


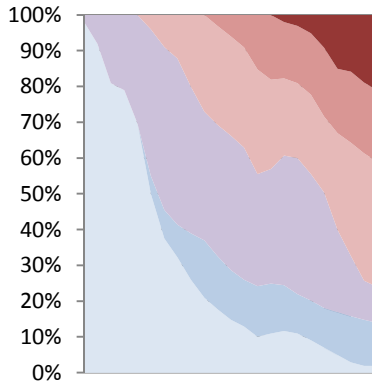
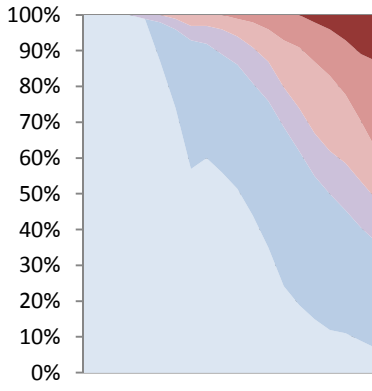
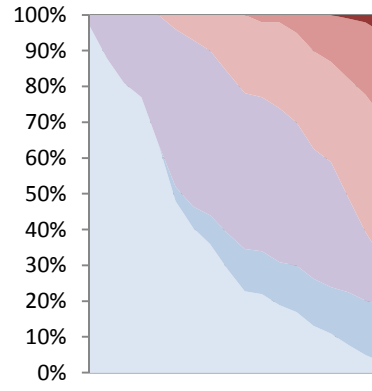
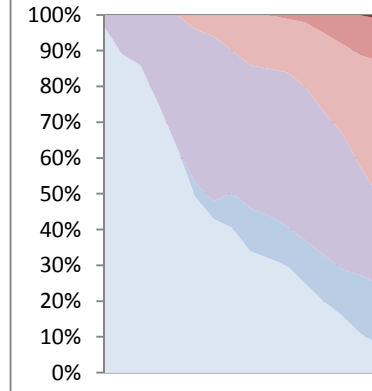
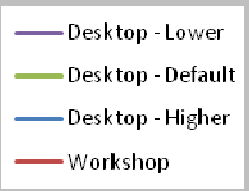
Figure A-4 Hydraulic Estimation for EWR E3BLY (Extrapolation)

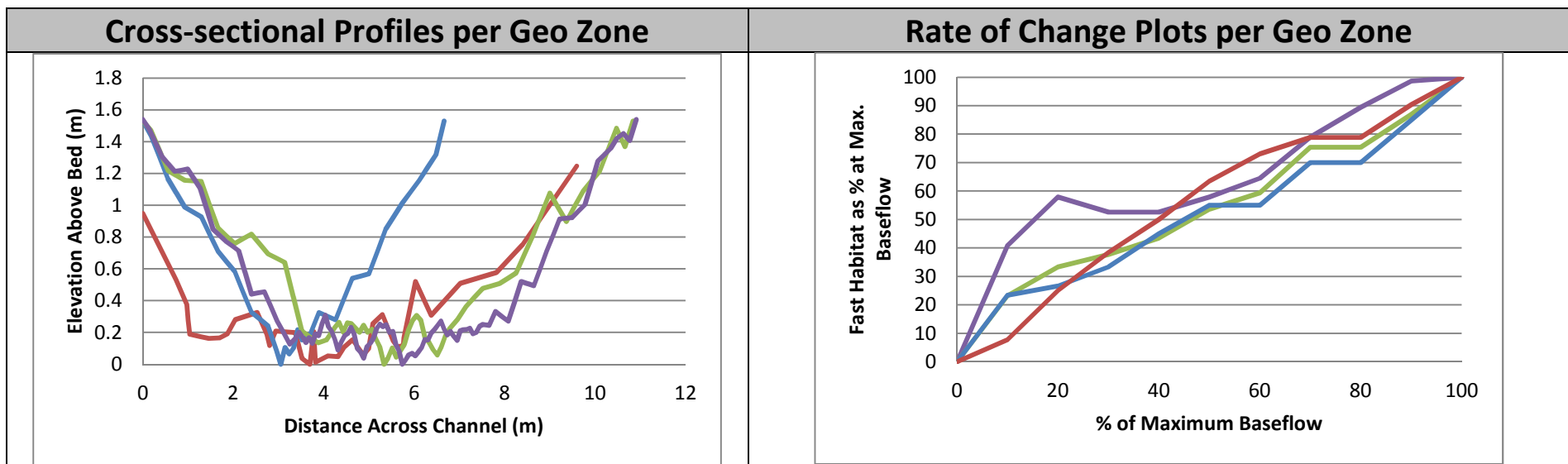
## APPENDIX B

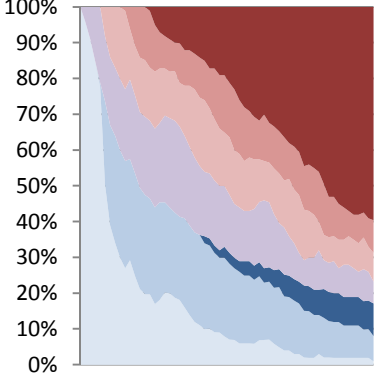
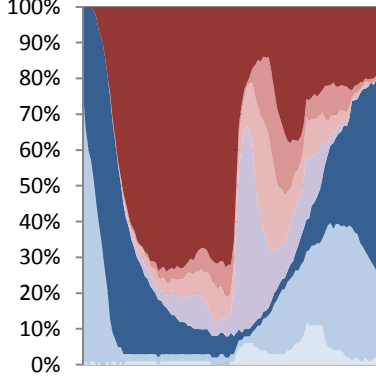
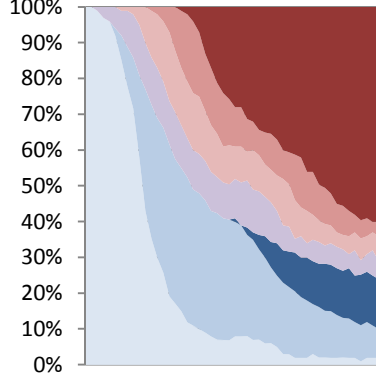
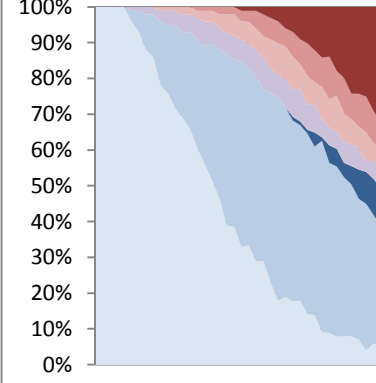


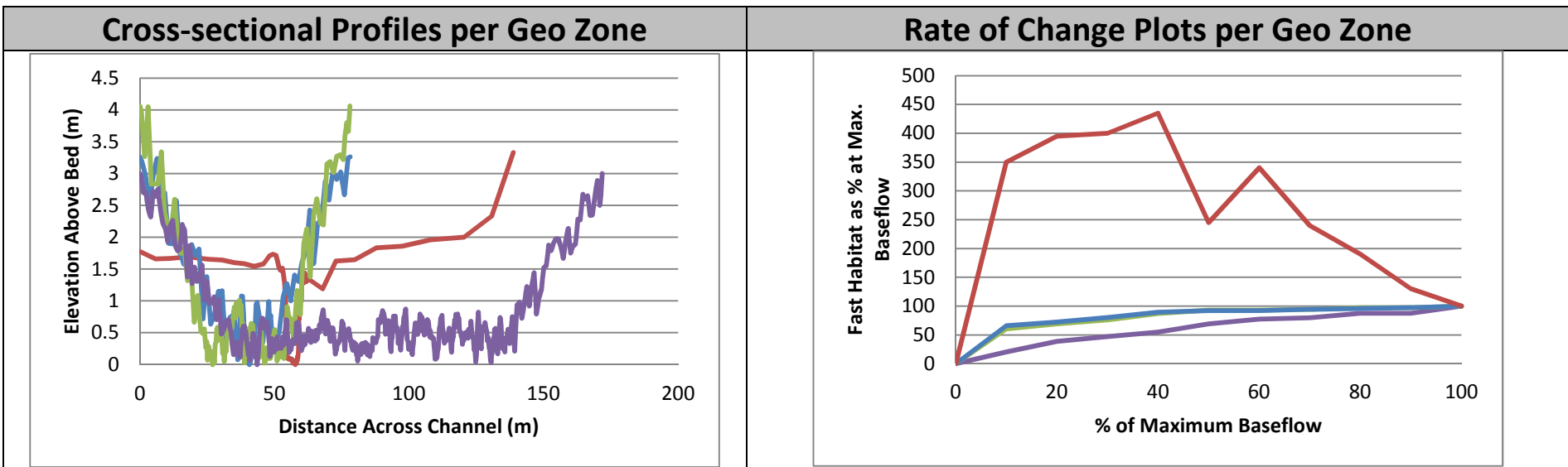
	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>E3BLY – Blystaanspruit (Crocodile)</b> 				
	<b>GEO ZONE</b>	B	C	C
<b>FAST HABITAT AREA</b>	30.50	15.75	21.13	17.38

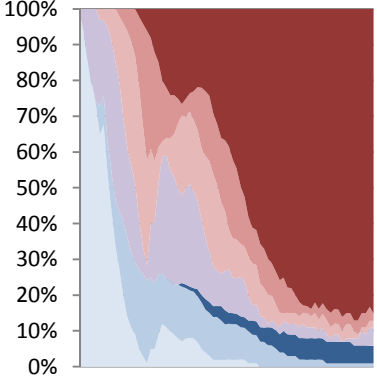
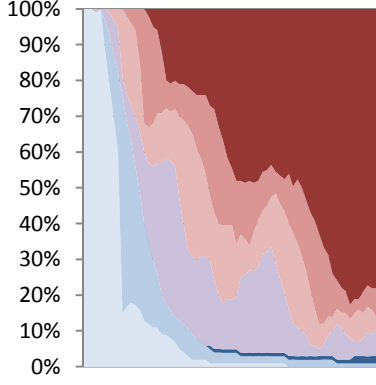
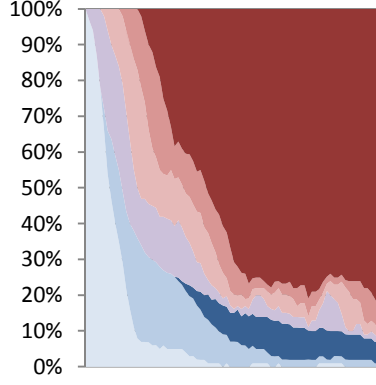
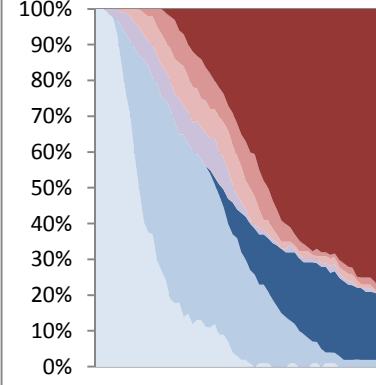


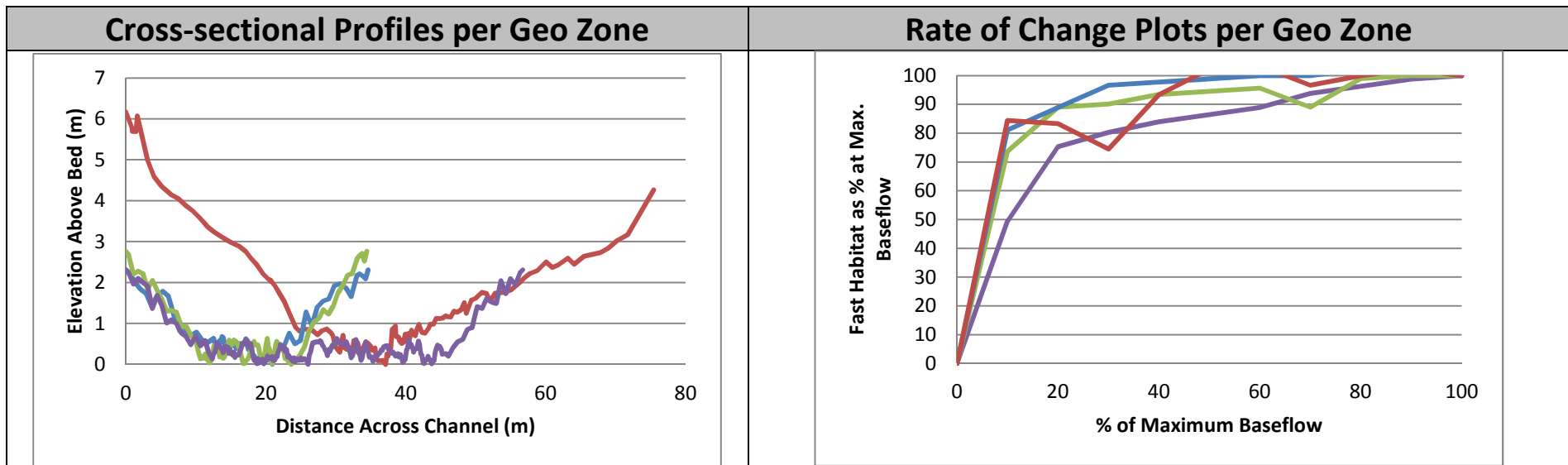
	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>E6SAB - Sabaan (Sabie)</b>				
	100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%	100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%	100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%	100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%
				
<b>GEO ZONE</b>	B	C	C	D
<b>FAST HABITAT AREA</b>	17.30	16.46	19.74	24.29

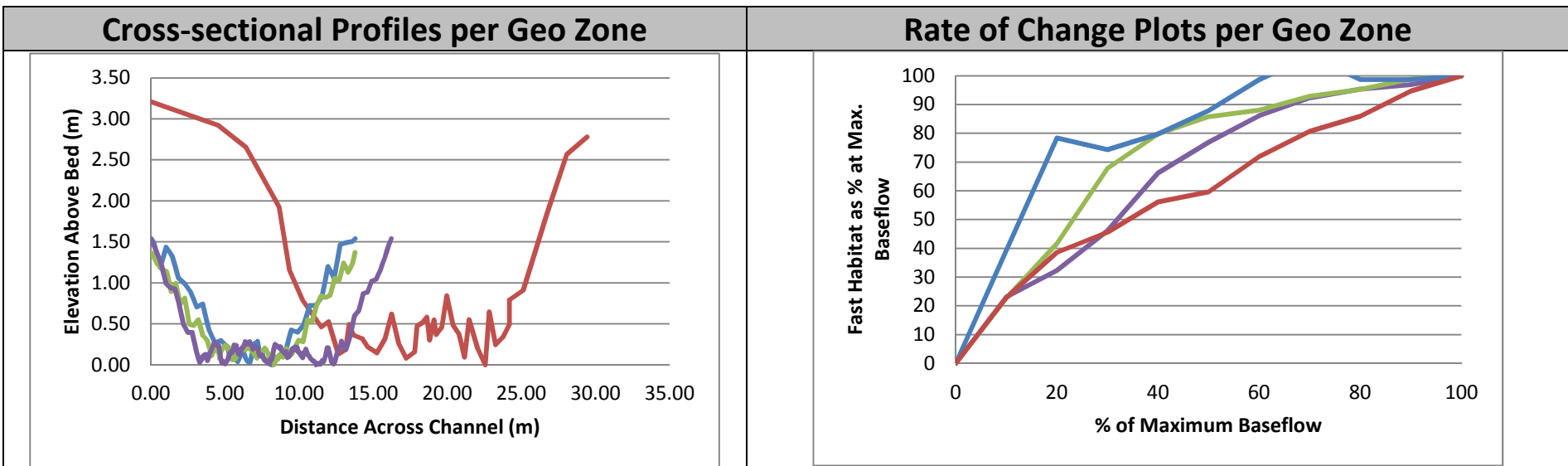
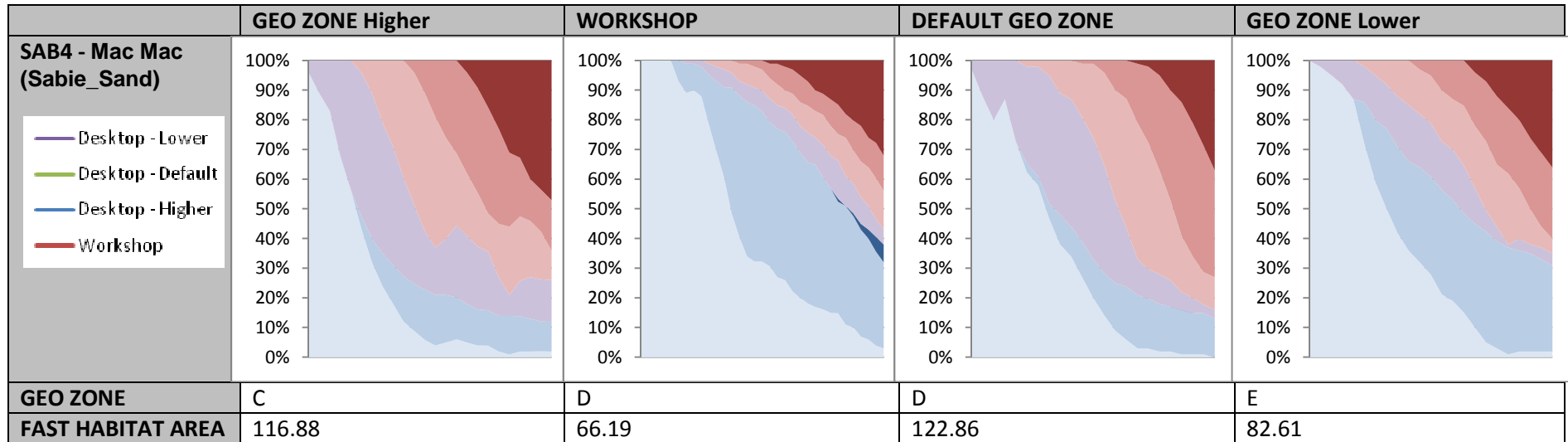


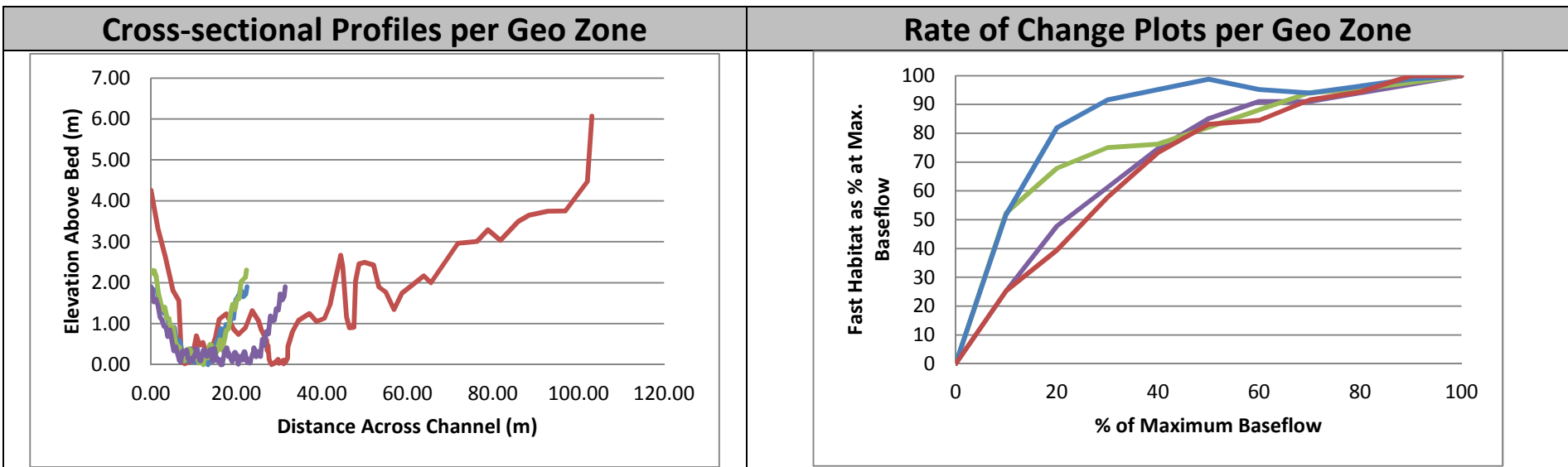
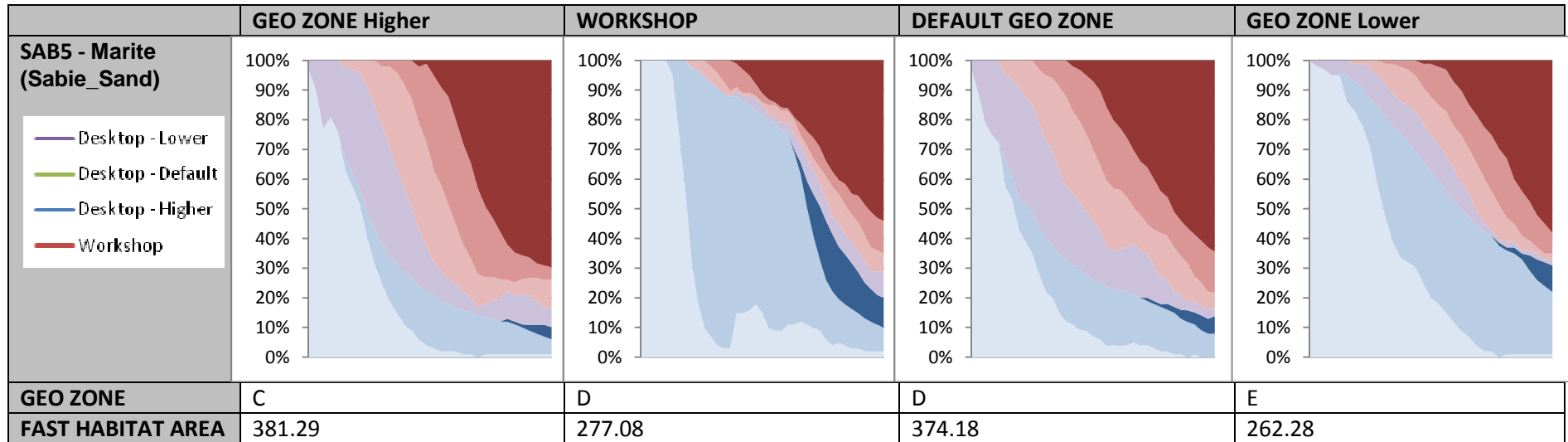
	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>CROC1 - Valyspruit (Crocodile)</b>				
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<b>GEO ZONE</b>	C	D	D	E
<b>FAST HABITAT AREA</b>	1014.90	849.52	936.67	475.91

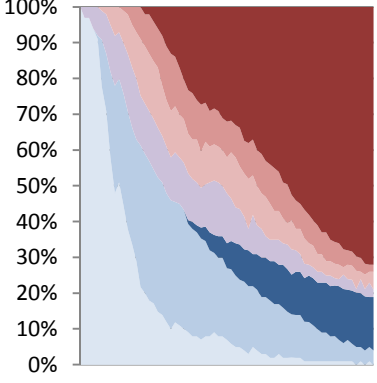
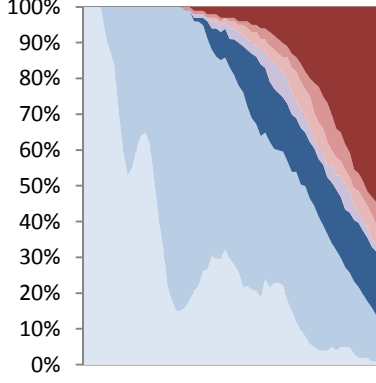
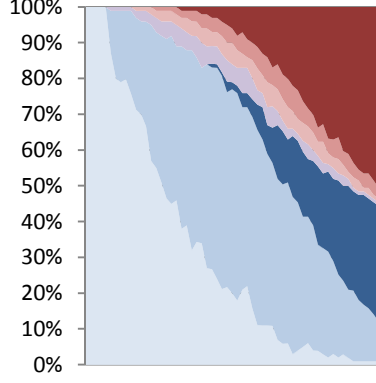
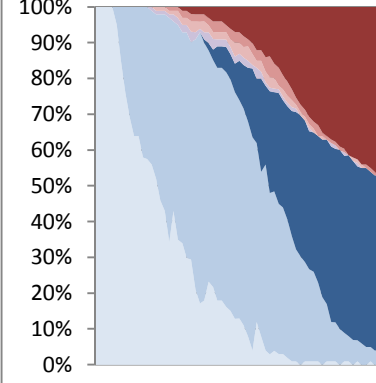


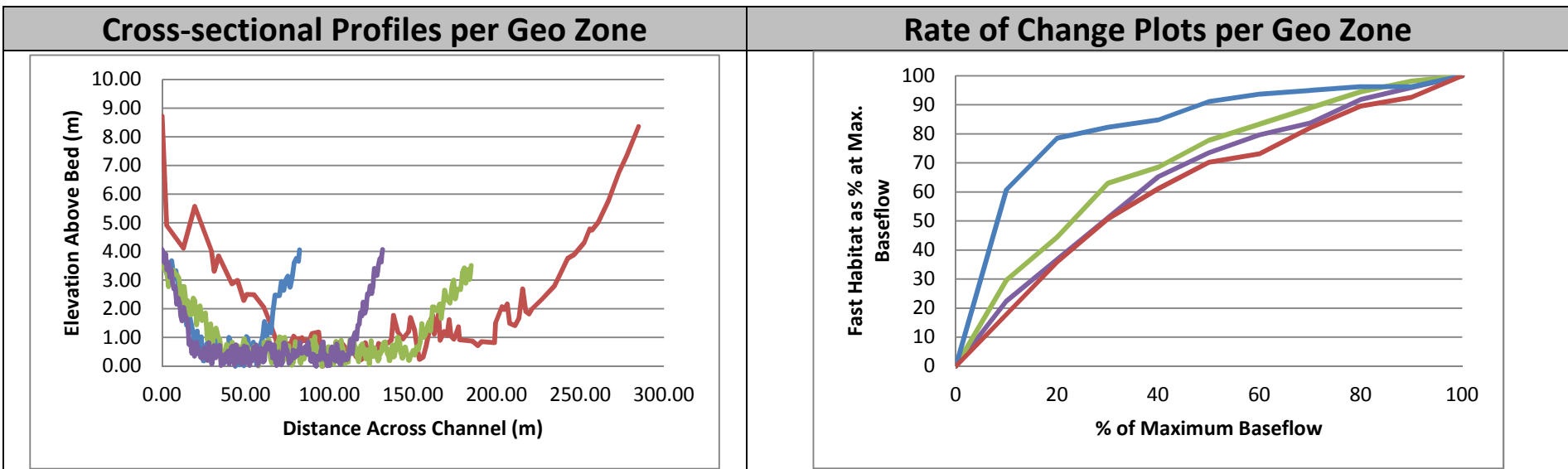
	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>CROC7 - Kaap (Crocodile)</b>				
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<b>GEO ZONE</b>	C	D	D	E
<b>FAST HABITAT AREA</b>	3243.92	3250.09	3159.23	2489.80

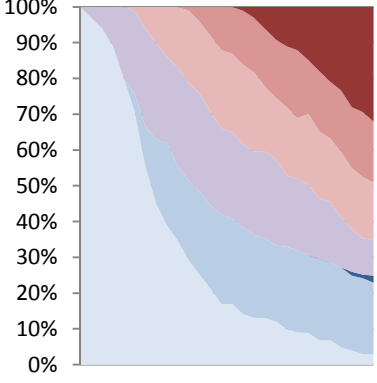
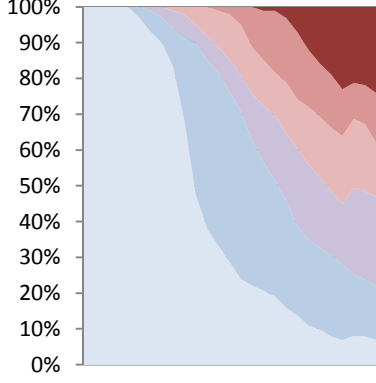
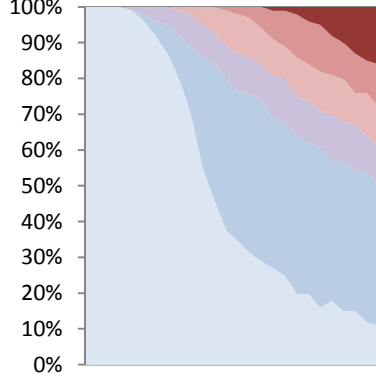
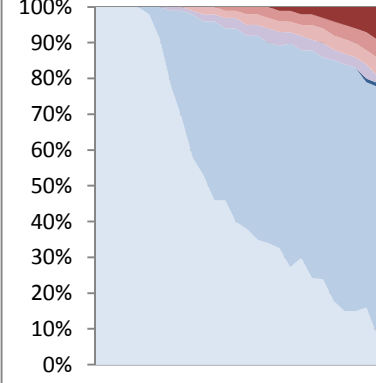


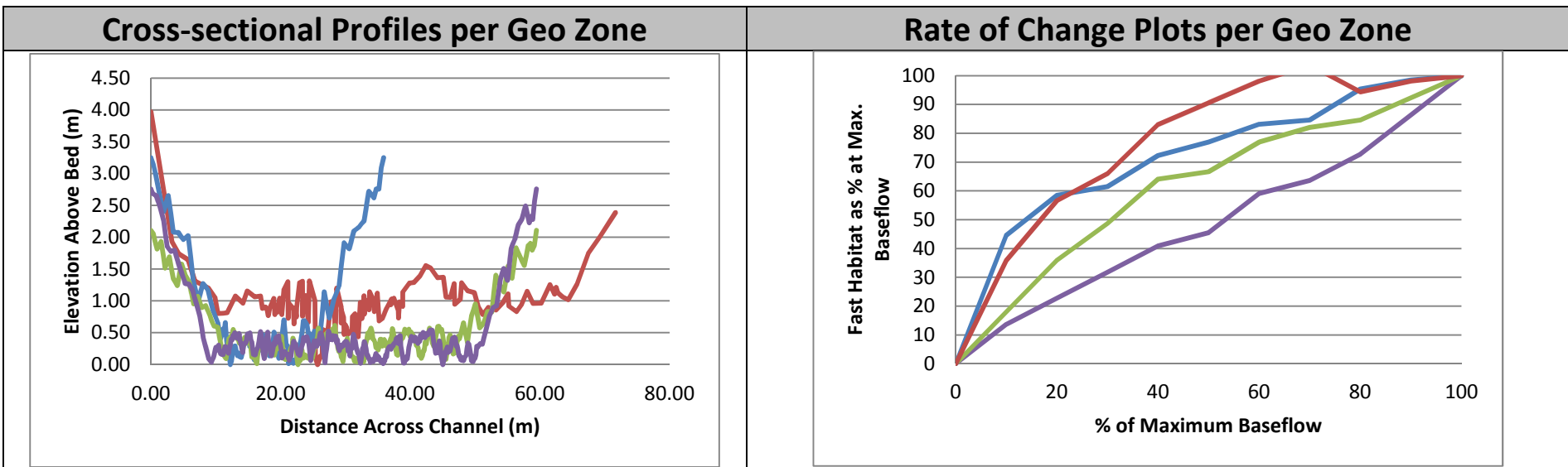


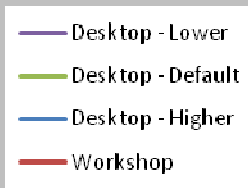
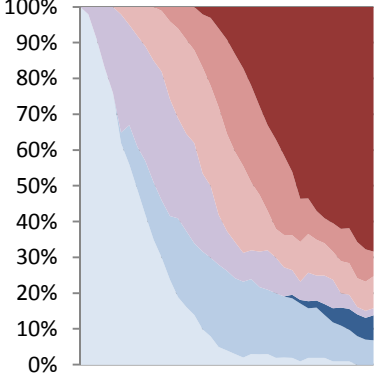
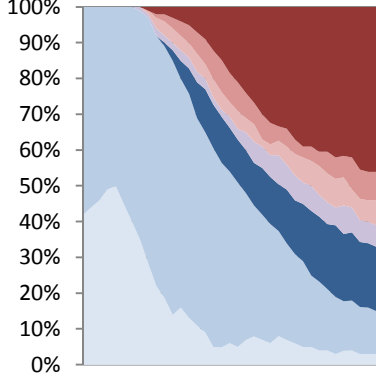
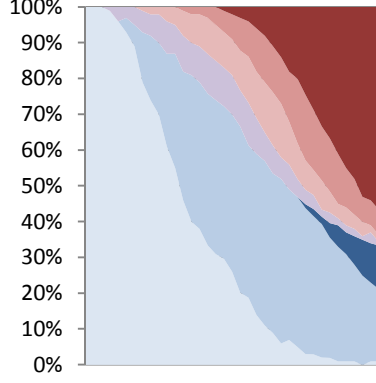
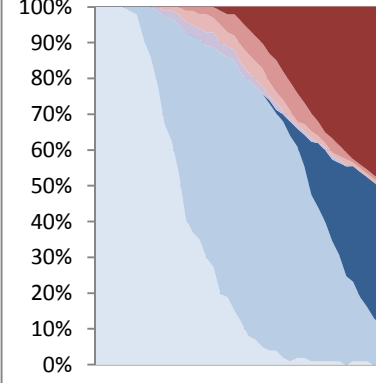


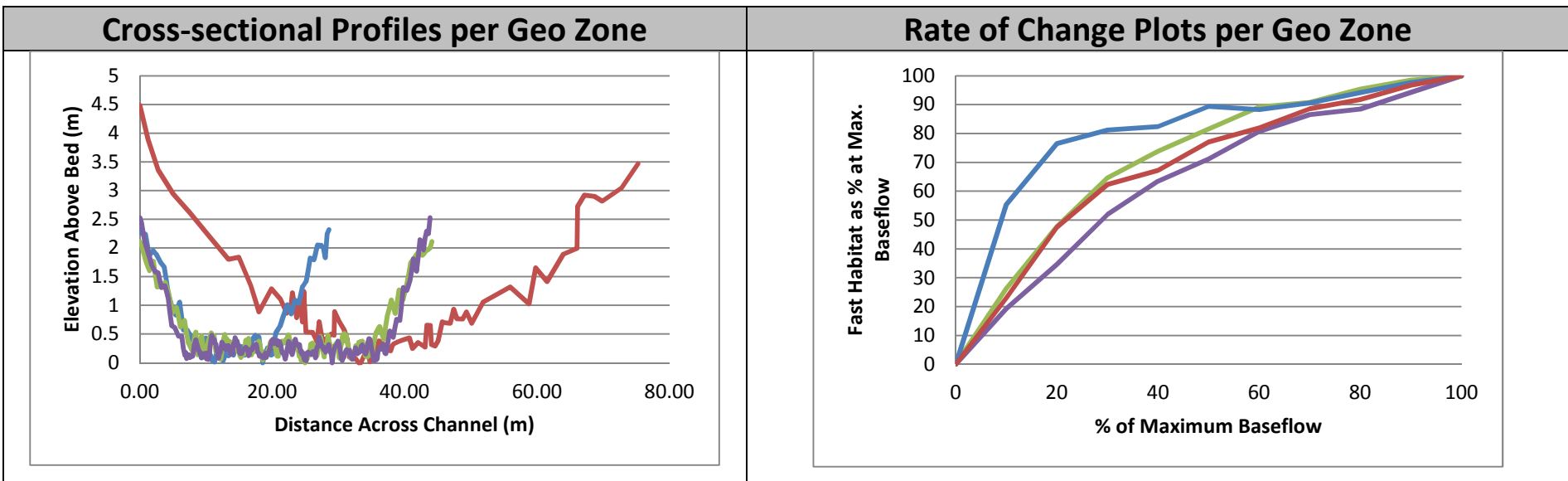
	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>CROC6 - Knongoma (Crocodile)</b>				
	<b>GEO ZONE</b>	D	E	E
<b>FAST HABITAT AREA</b>	2198.21	1415.56	1287.16	1089.03

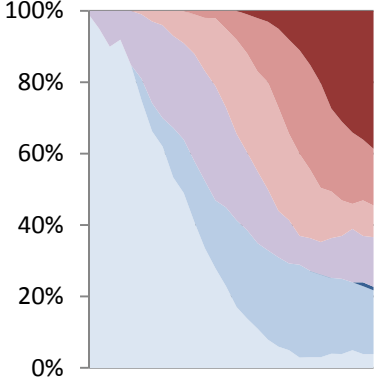
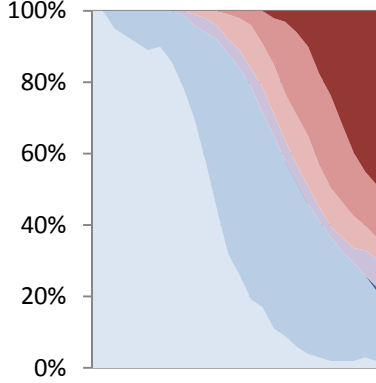
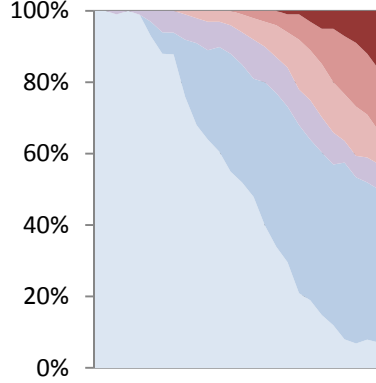
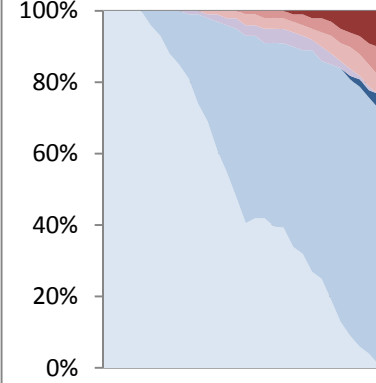


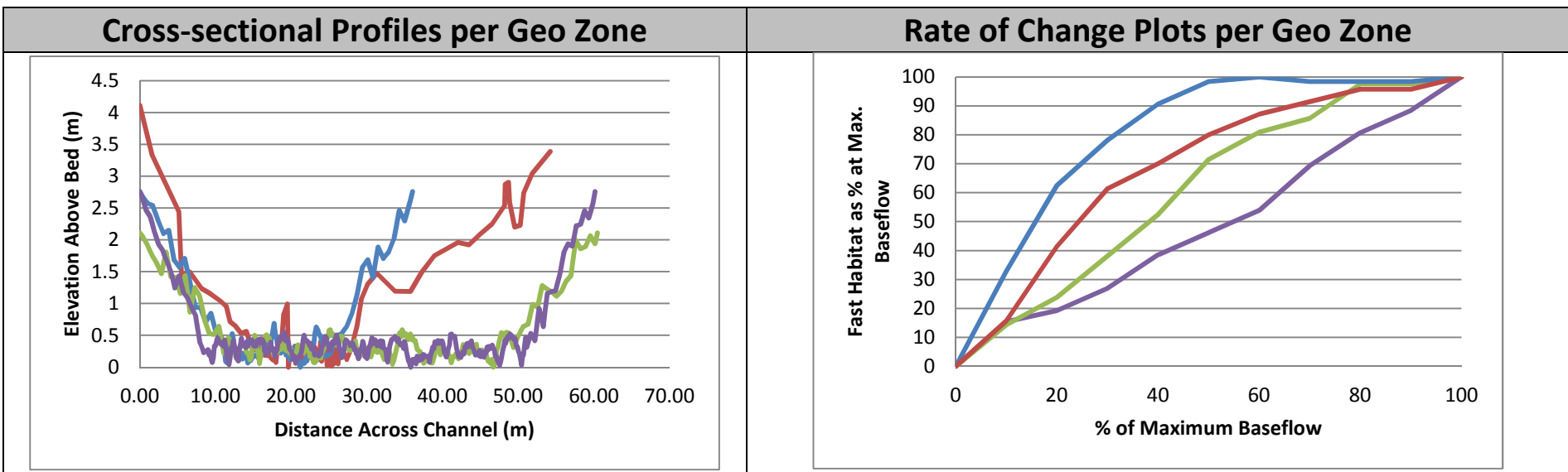
	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>MOK1 - Vaalwater (Mokolo)</b>				
<b>GEO ZONE</b>	D	E	E	F
<b>FAST HABITAT AREA</b>	124.80	109.09	69.18	28.26

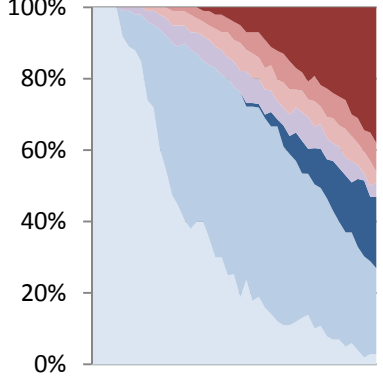
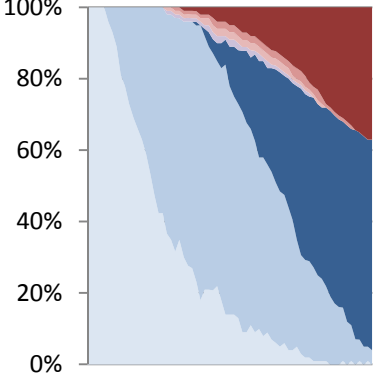
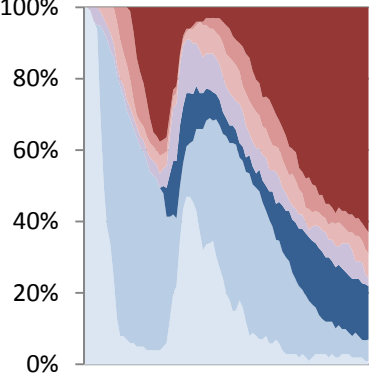


	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>MOK2 - Tobacco Farm (Mokolo)</b> 				
	<b>GEO ZONE</b>	D	E	E
<b>FAST HABITAT AREA</b>	515.44	327.49	349.50	260.18

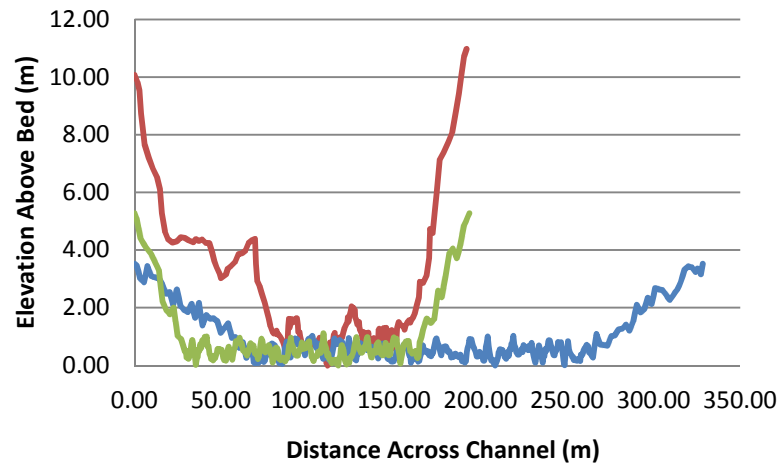


	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE	GEO ZONE Lower
<b>VAAL6 - Klip (Vaal)</b>				
<b>GEO ZONE</b>	D	E	E	F
<b>FAST HABITAT AREA</b>	165.86	161.284	83.15	40.35



	GEO ZONE Higher	WORKSHOP	DEFAULT GEO ZONE
<b>ORAN6 - Caledon (Orange)</b>			
<b>GEO ZONE</b>	E	F	F
<b>FAST HABITAT AREA</b>	1190.24	2034.73	800.52

**Cross-sectional Profiles per Geo Zone**



**Rate of Change Plots per Geo Zone**

