HYDRAULICS FOR DETERMINATION OF THE ECOLOGICAL RESERVE FOR RIVERS

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EXECUTIVE SUMMARY

BACKGROUND AND MOTIVATION

Water resources in South Africa are limited and their management and protection is critically important for the sustainable economic and social development of the country. Over the last 10 years an effort related to developing policies, structures and methodologies for the management and protection of South African water resources has been made. The Department of Water Affairs and Forestry and other agencies (including DEAT and the Department of Agriculture) responsible for natural resource management have been developing approaches for making decisions on resource protection and management (DWAF, 1999). A number of institutions and organizations, such as the Water Research Commission (WRC), Institute for Water Research (IWR), Southern Waters, Centre for Water in the Environment (CWE), Freshwater Research Unit, South African National Parks, Council for Scientific Industrial Research (CSIR), have contributed to research and development of methods and approaches related to protection of South African rivers.

As a result, a variety of new policies, tools, approaches and procedures have been developed including:

- The National Water Act
- The National Environmental Management Act
- The Water Law Principles
- The National Water Policy
- The Environmental Conservation Act
- The Conservation of Agricultural Resources Act
- The Integrated Environmental Management Procedure
- The South African Water Quality Guidelines for Aquatic Ecosystems
- Various environmental flow requirement methods
- The Index of Habitat Integrity
- The Fish Assemblage Integrity Index
- The South African Scoring System

- The National Aquatic Ecosystem Biomonitoring Programme (i.e. the River Health Programme)
- The South African Water Quality Guidelines for Domestic Use
- Resource Directed Measures for determining the ecological Reserve.

The National Water Act (No.36 of 1998) (NWA) has been developed to fundamentally reform the law relating to water resources. A major innovation of the Act is the incorporation of the concept of the Reserve. The Reserve consisted of two parts: "*Basic Human Needs Reserve*" and "*Ecological Reserve*". Implementation of the NWA requires that an ecological Reserve be determined for all significant resources, with those for which development is planned receiving priority attention. Ecological Reserve determination is an estimation of the environmental flow requirements (EFR) of different components of a river. It focuses on the amount of water required to maintain the system in a particular ecological condition. The estimation of flow for different aquatic components has required development of suitable methodologies and approaches.

In South Africa, activities addressing the development of holistic methods for assessing EFR of rivers were initiated in 1989 (King and Tharme, 1994). Since 1989, two comprehensive holistic methods namely the Building Block Methodology (BBM) and Downstream Response to Imposed Flow Transformations (DRIFT) as well as a more recent method, the Flow Stressor-Response (FS-R) (designed to be used on its own or as part of holistic methods such as the BBM and DRIFT), have been developed. These have to incorporate hydraulic analyses to provide the critical link between the hydrology and the other factors necessary to set the EFR.

Current methods of river hydraulics are, however, based to a large degree on principles that are more appropriate to high flows and flood analysis than the low flows characteristic of EFR. Furthermore, hydraulic characterization is generally limited to transects or cross-sections, and does not adequately describe conditions of river sites and/or river reaches. Most hydraulic analysis techniques currently used in EFR assessment were developed originally for engineering applications and many underlying concepts and procedures are inappropriate for environmental applications. There is consequently an urgent need to define the role of hydraulics within the context of EFR for rivers. This requires a fairly radical assessment of what hydraulic characterizations are important for assessing ecological functioning, and the development of appropriate methods for measuring, describing and predicting them.

OBJECTIVES

The statement of objectives as specified in the contract is as follows:

- **i.** To provide hydraulics methods to link hydrologic river characteristics and biotic requirements necessary for setting the ecological Reserve.
- **ii.** To provide hydraulic methods for the setting the Reserve when hydraulic data are limited.
- **iii.** To develop three-dimensional habitat modelling to assist in the determination of the ecological Reserve for rivers.
- **iv.** To develop an index of hydraulic characteristics for quantifying habitat availability.

CHAPTER ONE: Introduction

Researchers in environmental flows 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 (Rowlston et al, 2000). The results of hydraulic analyses and modelling therefore form the essential link between the way in which the hydrologists, engineers and water managers express the flow of water in the river in terms of flow rate, and the way in which river ecologists express the water requirements of the river ecosystem itself in terms of variables like the flow depth and velocity (Birkhead, 2002). The success and confidence with which flow requirements are assessed therefore depends to a large extent on the quality and reliability of the hydraulic information.

In South Africa, ecological flow determinations have relied on hydraulic information derived for two-dimensional cross-sections and single stage-discharge relationships. The limitations of hydraulic analyses employing single cross-sectional river profiles in Reserve determinations are used as a premise for developing methods that assess spatial changes in hydraulic characteristics across ”whole” geomorphological units. As the success and confidence with which flow requirements are assessed depends to a large extent on the quality and reliability of the hydraulic information, the main aim of this research is the development of improved modelling for hydraulic analyses for the determination of the ecological Reserve.

CHAPTER TWO: The Role of Hydraulics in the Determination of the Ecological Reserve for Rivers in South Africa

Ecological Reserve determination is an estimation of the flow requirements of different components of a river. It focuses on the amount of water required to maintain the system in a particular ecological condition. As habitats for different life history stages of aquatic animals are related to hydraulic parameters such as flow velocity and flow depth, it is required that the amount of water should be converted into such parameters. Hydraulic analyses are the key link in the ecological flow determination.

Determination of the ecological flow is a multidisciplinary procedure that requires development of methodologies suitable for this estimation. As a result of work of many specialists, a generic seven-step RDM methodology has been developed, as described in Water Resources Protection Policy Implementation: Resource Directed Measures for Protection of Water Resources, was developed (DWAF, 1999a). The level of detail or intensity of RDM determination is closely related to the ecological importance and sensitivity of the water resource, the scale and degree of the impact of proposed water use, and the urgency of the Reserve determination. There are four levels of RDM determination:

- Desktop
- Rapid
- Intermediate
- Comprehensive

The principles required to provide hydraulic information for different Reserve determinations are the same, regardless of the level. The difference between rapid, intermediate and comprehensive assessment lies in the amount of measured hydraulic data, and therefore in the accuracy of and confidence in the results produced. It is clear that greater confidence is expected for higher levels of determination (Birkhead, 2002).

In order to be successful in the determination of the ecological Reserve for the rivers in South

Africa, it is important to have a full understanding of the current process related to water resources protection. Improving understanding of the ecological flow requirements of river ecosystems, and developing and applying appropriate hydraulic methods are central to the process.

CHAPTER THREE: The Nature of Hydraulic Parameters and their Relationship to Biological Habitat

A growing need to provide more water services often conflicts with the desire to maintain or improve the ecological condition of the rivers for biodiversity and conservation goals. Modification of the natural flow regime affects both aquatic and riparian biota in streams and rivers. Ecological responses to the altered flow regime in a specific stream or river depend on how the components of flow have changed relative to the natural flow regime for that particular stream or river (Poff & Ward 1990), and how specific geomorphologic and ecological processes will respond to this relative change.

Impacts of modified flow on river biota have been reported widely (see for example Ward and Stanford, 1979, Cushman, 1985, Moog, 1993, and Ward and Stanford, 1995). Predictive capability regarding ecological impacts of human activities on ecological sustainability is a key factor in water management activities. Water resource management goals that sustain river ecology and socially and economically valuable goods and services are, therefore, a prime area of research and management (Richter et al, 1997). River management objectives related to ecosystem integrity cannot be met without maintaining a particular level of hydrological integrity. Flow is strongly correlated with the most important physicochemical factors in an ecosystem, which in turn, influences species richness, population dynamics, resilience and abundance (Poff and Ward, 1990). For effective and ecologically responsible river management, an understanding of aquatic habitats and links with the physical hydraulic parameters in rivers, such as flow depth and flow velocity, is essential.

Rivers and streams are flowing ecosystems, which function through the creation and maintainance of habitats for aquatic biota. Habitats are "places where individuals, populations, or assemblages can find the physical and chemical features needed for life. Habitat features include water quality, spawning sites, feeding areas, and migration routes"

(Bain and Stevenson, 1999). Diversity of aquatic habitat is therefore based on ecological flow. Furthermore aquatic habitats required for different life-history stages can be determined by flow velocity and flow depth. However average depth and velocity cannot describe the diversity of cross-sectional hydraulics. Descriptions of frequency distributions of velocity and depth as function of discharge are therefore preferred for recommending ecological flows for fish and macroinvertebrates.

CHAPTER FOUR: Hydraulics under Conditions of Large-Scale Roughness

Hydraulic analyses of the ecological flow requirements include consideration of the entire flow regime (ie. low and high flows). The hydraulics of low flows are more difficult to predict using the existing methods that are appropriate to conditions where flow resistance is through boundary shear along the channel perimeter. Hydraulics under low flows (where the flow depth and the height of the riverbed substrate elements are of the same order of magnitude) is referred to as hydraulics under conditions of large-scale roughness. Successful prediction of flow resistance by large-scale roughness depends on an understanding of the underlying phenomena as well as application of appropriate approaches for their description.

Flow resistance describes a process in river streams by which the physical shape, bed roughness of the channel and vegetation control the depth, width and mean velocity of flow in the stream. Theoretical aspects of open channel flow resistance are documented in some publications such as Leopold et al (1960), Rouse (1965), Bathurst (1982), and Yen (2002). The flow resistance in an open channel has four contributing components (Yen, 2002):

- Skin friction
- Form resistance
- Wave resistance
- Flow unsteadiness

Prediction of flow resistance in natural open channels is a complex task because of all the different sources of resistance as well as the influence of channel roughness that depends on relative submergence (the ratio of flow depth to height of roughness elements.) According to this ratio, the roughness can be divided into three roughness scales: large-scale, intermediate-scale and small-scale roughnesses (Bathurst et al 1981). The roughness is large-scale if the roughness elements affect the free surface, and the relative submergence is less than 1. The roughness is intermediate-scale if the relative submergence lies between 1 to 4. When the relative submergence is higher then 4, the roughness is small-scale and the roughness elements do not affect the water surface.

Although the complex phenomenon of flow resistance of large-scale roughness has a long research history, there is still today no reliable equation applicable for conditions where the flow depth and roughness elements height are of the same order of magnitude. Some of the equations were developed based on experimental or field data. Other equations were proposed as modifications of the well-known Manning, Ch⌈zy or Darcy-Weisbach equations. Application of all these equations requires an understanding of the limitations of their development.

CHAPTER FIVE: Hydraulic Characteristics Associated with Large-Scale Roughness - Laboratory Experiments

From the literature review (Chapter 4) it was found that in most cases, the development of the equations was based on laboratory or field data, representing more than one roughness scale. Other investigations have described three types of flow regime related to three (small, intermediate and large) scales (Lawrence, 1997; Lawrence, 2000; Nikora et al, 2001; Smart et al, 2002), and different modifications of the Darcy-Weisbach friction factor *f* for application to appropriate conditions have been proposed.

Modification of resistance coefficients such as Manning's *n*, the Chézy *C* and the Darcy-Weisbach *f*, (which were originally developed for small-scale roughness resistance) is not the only approach for predicting the flow resistance under large-scale and intermediate-scale roughness conditions. Laboratory experiments were therefore performed to gain a better understanding of flow resistance under large-scale roughness conditions.

The experiments were carried out in a laboratory flume under controlled and idealized conditions in order to understand the influence of the different resistance factors. The aim of the study was to establish the effects of large-scale elements on flow resistance under different hydraulic conditions determined by bed slope and discharge, as well as to develop resistance prediction methods. Different shapes and densities of roughness elements were tested.

CHAPTER SIX: Resistance Prediction for Streams with Large-Scale Roughness

Analysis of experimental data resulted in the development of new approaches for large and intermediate scale conditions.

When the channel bed material is large relative to the water depth, the flow resistance is exerted by the roughness elements' drag rather than boundary shear, and the resistance equations developed for estimation of small-scale roughness resistance are then not applicable. A different type of equation for prediction of the flow velocity, *V* has therefore been proposed, i.e.

$$V = \frac{1}{F}\sqrt{S} \qquad 1$$

with

$$F = \frac{1}{\sqrt{\frac{2g}{C_d nD}(A_t - n\,A_b)}} \qquad 2$$

in which *S* is the channel slope, *g* is gravitational acceleration, C_d is the roughness element drag coefficient, *n* is the number of roughness elements, *D* is the roughness element diameter, A_t is the considered bed area and A_b is the base bed area of individual roughness element.

Because the drag coefficient C_d depends on a number of variables, such as the Froude number, the Reynolds number, the roughness element shape and the relative depth, its estimation is not a simple procedure (Flammer et al, 1970). The experimental data (Chapter 5) were therefore used for development of a direct empirical formulation for the resistance coefficient *F* that does not include the drag coefficient C_d, i.e.

$$F = \left(\frac{W_{re}}{W_t}\right)^{0.255} \left(\frac{A_p}{A_b}\right)^{-0.465} \left(\frac{WS_{re}}{A_t}\right)^{0.374} \qquad 3$$

in which W_{re} is the volume of roughness elements within the considered flow element, W_t is the volume of the considered element, A_p is the projected cross-sectional area of the individual roughness element, A_b is the base bed area of the individual roughness element, WS_{re} is the wetted surface of roughness elements within the considered element, and A_t is the considered bed area. These equations were applied to the experimental data and results showed good agreement.

The roughness is of intermediate-scale if the relative submergence (the ratio of flow depth to roughness element height) lies between one and four. This regime represents a state of flow in which the surface roughness, as well as the frictional resistance, contributes to overall flow resistance, and the following equation for prediction of the flow velocity is proposed.

$$V = a\,\frac{1}{F}\sqrt{S} + (1-a)\frac{1}{n}R^{2/3}\sqrt{S} \qquad 4$$

In equation (4) n is Manning's resistance coefficient, and R is the hydraulic radius, with

$$a = 1.125\left(\frac{y}{h}\right)^{-1.777} \qquad 5$$

Equations (4) and (5) reproduced experimental (Bathurst et al 1981) and field data (Griffiths, 1981; Bathurst, 1985) well.

CHAPTER SEVEN: Modelling River Hydraulics for Determination of the Ecological Reserve

This chapter contributes to the overall aim of further developing the role of hydraulic in assessing ecological Reserves for rivers through: the use of "hydraulic indices" which are defined in terms of hydraulic habitat types for biota; the use of hydraulic analyses, coupled with digital terrain modelling and the mapping of substrate and vegetation, to compliment standard hydraulic information used in Reserve determinations; and the development of hydraulic software to assist analyses and provide integration with other components of the ecological Reserve.

The purpose of a "hydraulic index" is to provide a means for describing, in quantitative terms, the integrated hydraulic characteristics of a river reach, site or channel cross-section, in terms that are meaningful for ecologists to assess the response of biota to changes in flow. The use of habitat types has been developed within the framework of the Flow Stressor-Response method (O'Keeffe *et al,* 2002; O'Keefe and Hughes, 2004) but may also be used in holistic flow determination methods that require a semi-quantitative assessment of habitat suitability and abundance.

In South Africa, ecological flow determinations have relied on hydraulic information derived for two-dimensional cross-sections and single rating relationships. Three-dimensional spatial models are being used to provide more accurate characterisations of the physical and hydraulic templates, and improve the confidence in the assessments.

The framework for the hydraulic Reserve model, HERR (Hydraulics for the Ecological Rivers Reserve) has been developed and provided as an application of SPATSIM (SPatial And Time Series Information Modelling) developed at the Institute for Water Research (Hughes, 2004). HERR addresses various requirements highlighted during Reserve assessments, including, the need for software to assist with the analysis of data, particularly for lower levels of determination where limited measured data are available; to streamline the presentation of results; to provide greater conformity in the modelling approaches being used; and to provide a data-base for storing hydraulic information generated in ecological Reserve determinations.

CHAPTER EIGHT: Conclusions and Recommendations for Further Research

The purpose of this project is to improve the use of hydraulics for ecological Reserve determination in South Africa, and to provide guidance for hydraulic analyses necessary to relate a flow regime (in terms of discharge) to biotic response in a river.

Based on the results of this research, the following conclusions and recommendations for further investigation can be made:

- Hydraulic analyses required in the ecological Reserve determination are focused on the low-flow component of the hydrological regime, and sites are often characterized by large-scale roughness. Hydraulics under such conditions is complicated, and existing approaches for their description are inadequate (Chapter 4). New resistance equations distinguishing between large-scale and intermediate-scale roughness influences have therefore been developed (Chapter 6). The equations have been tested using experimental and field data, and have shown good results. This development will contribute to setting the Reserve at rapid and intermediate levels of determination when hydraulic data are limited. General application of the proposed equations (6.6) and (6.11) for estimating resistance with intermediate bed roughness sizes requires:

    - estimation of the large scale resistance coefficient F as a simple function of the bed material size characteristics, and
    - further verification of the proposed coefficient, a, that effects partitioning of the influences of the large and small roughness scales on flow resistance.

- Indices currently in use for translating hydraulic characteristics into biological habitat are dimensionless, and give no indication of absolute values of depth or velocity, and therefore cannot be used to assess the suitability of hydraulic characteristics for biota. A "hydraulic index" approach has been proposed to provide a way of describing, in quantitative terms, the integrated hydraulic characteristics of a river reach, site or channel cross-section, in terms that are meaningful for ecologists to assess the response of the biota to changes in flow (Chapter 7). The use of rule-based models for describing habitat conditions and biotic response shows promise, and deserves further investigation for ecological flow assessments.

- In order to provide more accurate characterizations of the physical and hydraulic templates, and to improve the confidence in the environmental flow assessment on a comprehensive level of the Reserve determination, a three-dimensional spatial modelling approach is being favoured in Reserve studies. A suite of three modelling tools, QuickSurf, RiverCAD and HECRAS, are being used for this purpose. This approach has previously been used with success in the hydraulic study of Nyl River

Floodplain (Birkhead *et al*, 2004). Further developments should re-introduce the use of GIS for post-processing and statistical analyses of hydraulic results.

- A framework for the hydraulic Reserve model, HERR, has been developed and is provided as an application of SPATSIM to address various requirements highlighted during Reserve assessments, including hydraulic analyses, presentation of results and storage of data.

- An ecological Reserve determination requires estimation of instream flow, which will maintain the aquatic habitats. The link between the aquatic habitats and the stream flow has been found through hydraulic modelling. Aquatic habitats required for different life-history stages can be determined by flow velocity and flow depth. However average depth and velocity can't describe the diversity of cross-sectional hydraulics. Further research in modelling of cross-sectional velocity distribution for a given discharge is therefore required for recommending ecological flows for fish and macroinvertebrates.

- Hydraulic habitat for macroinvertebrates is related to a near-bed flow regime determined by the substrate configuration and its influence on flow patterns and velocity in the near bed region. There are a number of different flow zones where velocities are different (Young, 1996). It was suggested that benthic macroinvertebrate communities may be influenced by turbulence rather than directly by velocities and associated drag forces (Bouckaert and Davis, 1998). In this connection future research related to the near-bed flow is suggested.

ATTAINMENT OF OBJECTIVES

The project achieved the objectives of the research as follows.

i. To provide hydraulics methods to link hydrologic river characteristics and biotic requirements necessary for setting the ecological Reserve

In the course of recommending ecological flow requirements, changes in discharge need to be related to changes in hydraulic characteristics such as flow depth and velocity, because biota do not respond to discharge per se, but rather to the hydraulic characteristics determined by the discharge together with the physical and vegetation characteristics of the river channel. The resistance equations developed for large-scale and intermediate-scale roughness conditions contribute significantly to the reliability of quantifying the relationship between discharge and hydraulic characteristics, and hence to the ability to set the ecological Reserve, especially for the rapid and intermediate levels of the Reserve determination. The objective has thus been met for dealing with certain conditions, but requires further work for others (e.g. very low flows and distributed vegetation influence).

ii. To provide hydraulic methods for the setting the Reserve when hydraulic data are limited

This objective is achieved by development of the framework for the HERR model. This software can be used to apply current level hydraulic analyses for Reserve determinations. It also provides a solid base for further software development and refinement to incorporate future advances in hydraulic methods, and to provide a modelling and data storage environment specifically appropriate for hydraulic analyses for Reserve Determinations in South Africa. Such developments could include

- integration of hydraulic analyses and graphical display with hydrological information,
- collation and inclusion of hydraulics data from previous IFR and Reserve studies,
- inclusion of probability models for predicting typical velocity distributions, and

- inclusion of new forms of resistance equations for large-scale roughness, typical of Reserve determination sites.

iii. To develop three-dimensional habitat modelling to assist in determination of the ecological Reserve for rivers

It was proposed to extend existing hydraulic analysis approaches to provide information on habitat availability across sites by incorporating three-dimensional physical mapping and employing hydroinformatics techniques based on digital terrain models (DTMs) and geographical information systems (GISs). It was intended to incorporate the geomorphological method concurrently being developed by Wadeson and Rowntree (in press) for describing discharge related changes in instream habitat using hydraulic biotope mapping. Mapping of hydraulic biotopes provides useful visual information on the spatial distribution of different hydraulic habitats and their frequency distributions, but the method is problematic in some respects (Chapter 7). A new approach based on three modelling tools, QuickSurf, RiverCAD and HECRAS, has been therefore developed to provide habitat modelling for determination of the ecological Reserve for rivers; this approach meets the stated objective.

iv. To develop an index of hydraulic characteristics for quantifying habitat availability

Existing indices for translating hydraulic characteristics into biological habitat are dimensionless, and give no indication of absolute values of depth or velocity, and therefore cannot be used to assess the suitability of hydraulic characteristics for biota (Chapter 7). A "hydraulic index" has therefore been developed to provide a way of describing, in quantitative terms, the integrated hydraulic characteristics of a river reach, site or channel cross-section, in terms that are meaningful for ecologists to assess the response of the biota to changes in flow.

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The Steering Committee responsible for this project consisted of the following persons:

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LIST OF SYMBOLS AND ABBREVIATIONS

BBM	Building Block Methodology
CAD	Computed Aided Drawing
CAM	Catchment Management Agencie
CSIR	Council for Scientific Industrial Research
CWE	Centre for Water in the Environment
DRIFT	Downstream Response to Imposed Flow Transformation
DSS	Decision Support System
DTM	Digital Terrain Model/Modelling
DWAF	Department of Water Affairs and Forestry
EC	Ecological Category
EFR	Ecological Flow Requirement
FCS	Fast flow over/around Coarse Sediment
FD	Fast and Deep
FS	Fast and Shallow
FV	Fast flow through Vegetation
GIS	Geographical Information System
GPS	Global Positioning System
GRD	GRiD
HEC-RAS	Hydrological Engineering Centre - River Analysis System
HEP	Habitat Evaluation Procedure
HERR	Hydraulics for the Ecological Rivers reserve
H-FS-R	Habitat-Flow Stressor-Response
HIVEL	HIgh Velocity
HSI	Habitat Suitability Index
HU	Habitat Unit
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
IWR	Institute for Water Research
LIDAR	LIght Detection And Ranging
LLD	local Log-density
LLD	Local Log-Density

MDS	Minimum Desirable Streamflow
NWA	National Water Act
PHABSIM	Physical Habitat Simulation Model
PHABSIM	Physical HABitat SIMulation System
RMA	Resource management Association
RDM	Resource-Directed Measures
RQOs	Resource Quality objectives
SCS	Slow flow over/around Coarse Sediment
SD	Slow and Deep
SFS	Slow flow over Fine Sediment
SMS	Surfacewater Modelling System
SPATSIM	SPatial And Time Series Information Modelling
SS	Slow and Shallow
SV	Slow flow through Vegetation
TGRD	Triangulated GRiD
TIN	Triangulated Irregular Network
WRC	Water Research Commission

1d	one-dimensional
2d	two-dimensional
3d	three-dimensional
$\overline{V_i}$	average approach velocity to the i^{th} plant
ρ	fluid density
ν	fluid dynamic viscosity (ft^2/s)
γ	specific weight of fluid
τ_0	shear stress at the boundary
λ_1	roughness spacing
α_I	preference value for an I^{th} subunit type (of *m* types) at a particular site 1 (exponential distribution),
a	coefficient related to the relative submergence
A	cross sectional area of the object normal to the flow
A	frontal area of an individual plant blocking flow
a	dimensionless coefficient

A_*	net submerged frontal area of a partially submerged plant
a,b	spacing
A_b	base area of the roughness elements
AD	average discharge
A_p	projected cross-sectional area of the individual roughness element
$\overline{V}$	approach velocity
A_s	total cross sectional area of the stem of an individual plant
A_t	considered bed area
A_w	total wetted roughness cross-sectional area
b	effective roughness concentration
b	slope of a plot of v versus V(v)on log-log scale
C	Chézy resistance coefficient
c	shape parameter equal to 1/b, and
C_d	drag coefficient
C_D	stem drag coefficient
C_v	the centroid for diversity and current velocity (v)
C_x	large scale roughness resistance coefficient
d	areal density of the species
D	averaged dominant roughness
D	particle diameter
D	roughness element diameter
D	stem diameteter
D_g	sediment characteristic
d_x	size dimension on flow direction
d_y and d_z	width and height of roughness element respectively
d_{y50}	roughness element cross-stream axis
E_s	modulus of plant stiffness
f	Darcy-Weisbach friction factor
F	resistance coefficient
f_b	friction factor (bed)
F_d	drag force of the roughness elements
Fr	Froude number
g	gravitational acceleration
h	roughness height

H	average undeflected plant height (ft)
H	averaged reach depth
k	representative sediment size
k_n	unit conversion for Manning's equation
k_s	Nikuradse roughness
L	channel length
M	relative plant density (number of plants per ft^2)
m	correction factor for meandering of the channel
n	number of roughness elements
n_1	correction factor for the effect of surface irregularities
n_2	value of variations in shape and size of the channel cross section
n_3	value for obstructions
n_4	value for vegetation and flow conditions
n_b	Manning's boundary roughness coefficient, excluding the vegetation
P	Velocity profile parameter
Q	discharge
R	hydraulic radius
$R^{/}$	effective hydraulic radius
R_b	hydraulic radius (bed)
Re	Reynolds number
R_f	hydraulic radius (flume)
r_i and n_i	the proportions of the I^{th} subunit type in cells used by fish in all cells within the site respectively
S	longitudinal slope
s	is the cross-stream groove width
s	shape parameter of the point velocity distribution
s_1 and s_2	shape related factors
t	mixing parameter varying from 0 (normal distribution) to
U	averaged reach velocity
u	point velocity
u	velocity at distance z across the wake
V	average flow velocity
v	local flow velocity,
V	maximum cross-sectional velocity, and

w	channel width
w	object width in z direction
w	surface width of the flow
W	width of average plant (ft)
W_{re}	volume of roughness elements within the considered flow element
WS_{re}	wetted surface of the roughness elements within the considered element
W_t	volume of the considered element
x	relative point velocity, equal to u/U
x	relative depth, equal to h/H (h is flow depth, and H is mean reach depth).
y	flow depth
y'	depth from a free surface to a bed datum level
λ	large roughness elements concentration
τ_r	effective shear stress due to drag of the discrete roughness elements
τ_s	shear stress on the background surface
$\sum A_i$	projected vegetation area in the streamwise direction

Chapter 1

INTRODUCTION

1.1 Background

Water resources in South Africa are limited and their management and protection is, apart from any biodiversity considerations, critically important for the sustainable economic and social development of the country. Over the last decade, much effort has been devoted to developing policies, structures and methodologies for the management and protection of South African water resources. New ways of applying information and making decisions on resource protection and management have been under development at the Department of Water Affaires and Forestry (DWAF, Resource Quality Services), and by other agencies responsible for natural resource management (DWAF, 1999). A number of institutions and organizations are contributing to research and development of methods and approaches related to protection of South African rivers, such as the Water Research Commission (WRC), Institute for Water Research (IWR) (Rhodes University), Southern Waters cc, Centre for Water in the Environment (CWE) (University of the Witwatersrand), Freshwater Research Unit (University of Cape Town), South African National Parks, Council for Scientific Industrial Research (CSIR).

The National Water Act (No.36 of 1998) (NWA) has been developed to provide a fundamental reform of the law relating to water resources. Implementation of the NWA requires that an Ecological Reserve (the Ecological Reserve is part of Reserve which includes the Basic Human Needs Reserve) be determined for all significant resources, with those for which development is planned receiving priority attention.

Determination of the Ecological Reserve is a complex procedure requiring involvement of a wide range of experts such as aquatic scientists, social scientists, hydrologists, geomorphologists, hydraulicians, engineers and resource economists. Understanding of instream flow requirements of river ecosystems, and development and applications of appropriate methods to determine them are central to the whole process.

Ecological Reserve determination is the estimation of flow requirements of different components of a river. It focuses on the amount of water required to maintain the system in a particular ecological condition. Researchers in environmental flow 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 (Rowlston et al, 2000). The results of hydraulic analyses and modelling therefore form the essential link between the way in which the hydrologists, engineers and water managers express the flow of water in the river in terms of flow rate, and the way in which river ecologists express the water requirements of the river ecosystem itself in terms of variables like the flow depth and velocity (Birkhead, 2002).

In South Africa, ecological flow determinations have relied on hydraulic information derived for two-dimensional cross-sections and single stage-discharge relationships. The limitations of hydraulic analyses employing single cross-sectional river profiles in Reserve determinations are used as a premise for developing methods that assesses spatial changes in hydraulic characteristics across ”whole” geomorphological units.

As the success and confidence with which flow requirements are assessed depends to a large extent on the quality and reliability of the hydraulic information, the main aim of this research is the development of improved modelling for hydraulic analyses for the determination of the ecological Reserve.

1.2 Project Objectives

Based on this background, the objectives of the research were originally proposed as follows.

- To provide hydraulics methods to link hydrologic river characteristics and biotic requirements necessary for setting the ecological Reserve.
- To provide hydraulic methods for the setting the Reserve when hydraulic data are limited.
- To develop three-dimensional habitat modelling to assist in the determination of the ecological Reserve.
- To develop an index of hydraulic characteristics for quantifying habitat availability.

The objectives have been addressed by undertaking literature survey, laboratory investigations in the Hydraulic Laboratory in the School of Civil and Environmental Engineering at the University of the Witwatersrand, data analyses, theoretical development and computer modelling.

1.3 Layout

This report details the research undertaken to address the above objectives.

Chapter 2 presents a review of South African national policy on the protection of rivers as well as international and South African methodologies used in ecological flow requirement determination. The chapter focuses on the role of hydraulics in the determination of the ecological Reserve for rivers in South Africa. **Chapter 3** reviews published information related to hydraulic parameters and its relationship to biological habitat. **Chapter 4** reviews equations and approaches developed internationally for prediction of flow resistance under different conditions of relative submergence. **Chapter 5** describes experimental work to investigate the influence of large- and intermediate-scale roughnesses on overall flow resistance under different hydraulic conditions. **Chapter 6** presents theoretical development of an appropriate form of the resistance equations for large-scale and intermediate-scale roughnesses. The proposed equations were examined using results derived from the experimental work as well from the literature. **Chapter 7** addresses the modelling of river hydraulics for determination of the ecological Reserve. This chapter contributes to the main objectives of the project through (a) the use of “hydraulic indices”, which are defined in terms of hydraulic habitat types for biota, (b) the use of hydraulic analyses, coupled with digital terrain modelling and the mapping of substrate and vegetation, to complement standard hydraulic information used in reserve determinations, and (c) the development of hydraulic software to assist analyses and provide integration with other components of the ecological reserve. **Chapter 8** presents conclusions of the project and recommendations regarding further research.

Chapter 2

The Role of Hydraulics in the Determination of the Ecological Reserve for Rivers in South Africa

2.1 National Policy on the Protection of Rivers in South Africa

Water resources in South Africa are limited and their management and protection is critically important for the sustainable economic and social development of the country. Over the last 10 years an effort related to developing policies, structures and methodologies for the management and protection of South African water resources has been made. The Department of Water Affairs and Forestry and other agencies (including DEAT and the Department of Agriculture) responsible for natural resource management have been developing approaches for making decisions on resource protection and management (DWAF, 1999). A number of institutions and organizations, such as the Water Research Commission (WRC), Institute for Water Research (IWR), Southern Waters, Centre for Water in the Environment (CWE), Freshwater Research Unit, South African National Parks, Council for Scientific Industrial Research (CSIR), have contributed to research and development of methods and approaches related to protection of South African rivers.

As a result, a variety of new policies, tools, approaches and procedures have been developed including:

- The National Water Act;
- The National Environmental Management Act;
- The Water Law Principles;
- The National Water Policy;
- The Environmental Conservation Act;
- The Conservation of Agricultural Resources Act;
- The Integrated Environmental Management procedure;
- The South African Water Quality Guidelines for Aquatic Ecosystems;
- Various environmental flow requirement methods
- The Index of Habitat Integrity
- The Fish Assemblage Integrity Index;

- The South African Scoring System;
- The National Aquatic Ecosystem Biomonitoring Programme (ie, the River Health Programme);
- The South African Water Quality Guidelines for Domestic Use;
- Resource Directed Measures for determining the ecological Reserve.

The National Water Act (No.36 of 1998) (NWA) has been developed to provide a fundamental reform of the law relating to water resources. The NWA views the river as a "resource" rather than a "user" of water. The term resource "*is used to include the health of all parts of the water resources, which together make up an ecosystem, including plant and animal communities and their habitats*" (DWAF, 1997; DWAF, 1998). The Act is revolutionary because it recognises the central role of ecosystems in water supply. Sustainability and equity are identified as central guiding principles of the Act in the protection, use, development, conservation, management and control of water resources.

In the Act the main provisos affecting the way water resources are managed are:

- The development of a national water resource strategy;
- The development of catchment management strategies;
- Protection of the water resources by developing a classification system and setting resource quality objectives;
- Determination of the Reserve;
- Monitoring of the water resource.

<u>National Water Resource Strategy</u>

To facilitate the proper management of water resources the National Water Resource Strategy (NWRS), as the implementation framework for the NWA, was proposed with four main objectives:

- To establish the national framework for managing water resources;
- To establish the framework for the preparation of catchment management strategies;
- To provide information, and
- To identify development opportunities and constraints.

For further management of water resources in an integrated manner at regional level, South African water resources were divided into 19 water management areas under catchment management agencies (CMAs) (Government Notice No. 1160, 1999). The CMAs have the following responsibilities:

- Development of a catchment management strategy, and
- Management of water resources.

<u>Catchment Management Strategy</u>

The Catchment Management Strategy has to set principles for allocating water to existing and prospective users, taking into account all matters relevant to the protection, use, development, management and control of water resources.

<u>Protection of water resources</u>

Protection of water resources ensures their availability for human use as well as maintaining their ecological functioning. To achieve the aim, application of two additional approaches are proposed (DWAF, 1999):

- Resource-Directed Measures (RDM), and
- Source-Directed Controls.

RDM focus on resource quality in terms of the health or integrity of water resources, including their water quantity and water quality, in-stream and riparian habitats, and condition and distribution of the aquatic biota.

RDM include the following components:

- Development of a National Classification System;
- Determination of the class of specific water resources;
- Establishment of resource quality objectives, and determination of the Reserve, with reference to the relevant class.

Source directed controls deal with implementation of appropriate management of water uses including:

- Best management practice measures that apply nationally.
- Special measures, derived from catchment management strategies and/or plans.
- Site specific measures, stemming from the authorisation process, taking account of

considerations specific to the water use being considered.

Water resources classification system and resource quality objectives

The first stage in the protection process is the development of a system, which provides guidelines and procedures for classifying water resources into classes and setting of resource quality objectives (RQOs). Under such classification system, water resources can be grouped into classes representing different levels of protection. The proposed classification system for water resources in South Africa has 4 classes, A to D that would range from close to natural to largely modified.

The RQOs are scientifically derived criteria, based on the best available scientific knowledge and understanding. The main aim of the RQOs is to provide a desired level of water resource protection (DWAF, 1999).

The RQOs for aquatic ecosystems has four components:

- Water quantity;
- Water quality;
- Habitat integrity, and
- Biotic integrity

Determination of the Reserve

The NWA provides for river's ecological requirements founded on environmental flows, which will maintain ecological structure and function, channel, bed and floodplain form, function and connectivity, and a measure of its natural flow characteristics. Implementation of the NWA requires that an ecological Reserve be determined for all significant resources, with those for which development is planned receiving priority attention.

Ecological Reserve determination is an estimation of the flow requirements of different components of a river. It focuses on the amount of water required to maintain the system in a particular ecological condition. The estimation of flow required for different aquatic components is a complex procedure, and development of methodologies suitable for this estimation, was therefore required. As a result of work of many specialists, a generic seven-step RDM methodology was developed, as described in Water Resources Protection Policy

Implementation: Resource Directed Measures for Protection of Water Resources (DWAF, 1999a):

Step 1: Initiate the RDM study
Step 2a: Determine the ecological type of each resource
Step 2b: Delineate resource units within the study area
Step 2c: Select survey sites within the study area
Step 3: Determine the reference conditions for each resource unit
Step 4a: Assess the present status of the resource units
Step 4b: Assess the ecological importance and sensitivity of the resource units
Step 5: Set the management class for each resource unit
Step 6a: Quantify the Reserve for each resource unit
Step 6b: Set resource quality objectives for each resource unit
Step 7: Design an appropriate resource monitoring programme

The level of detail or intensity of RDM determination is closely related to the ecological importance and sensitivity of the water resource, the scale and degree of the impact of proposed water use, and the urgency of the Reserve determination. There are several factors, which influence the selection of the level of RDM determination. Graphical interpretation of the rules for the selection of the level of RDM determination is shown in Figure 2.1 (DWAF, 1999a).

Determination of the Ecological Reserve is a complex procedure required involvement of wide range of experts such as aquatic scientists, social scientists, hydrologists, geomorphologists, hydraulicians, engineers and resource economists. Understanding of instream flow requirements of river ecosystems, and development and applications of appropriate methods are inalienable parts of the whole process. Discussion on international and South African methodologies and methods related to instream flow requirements application is therefore presented below.

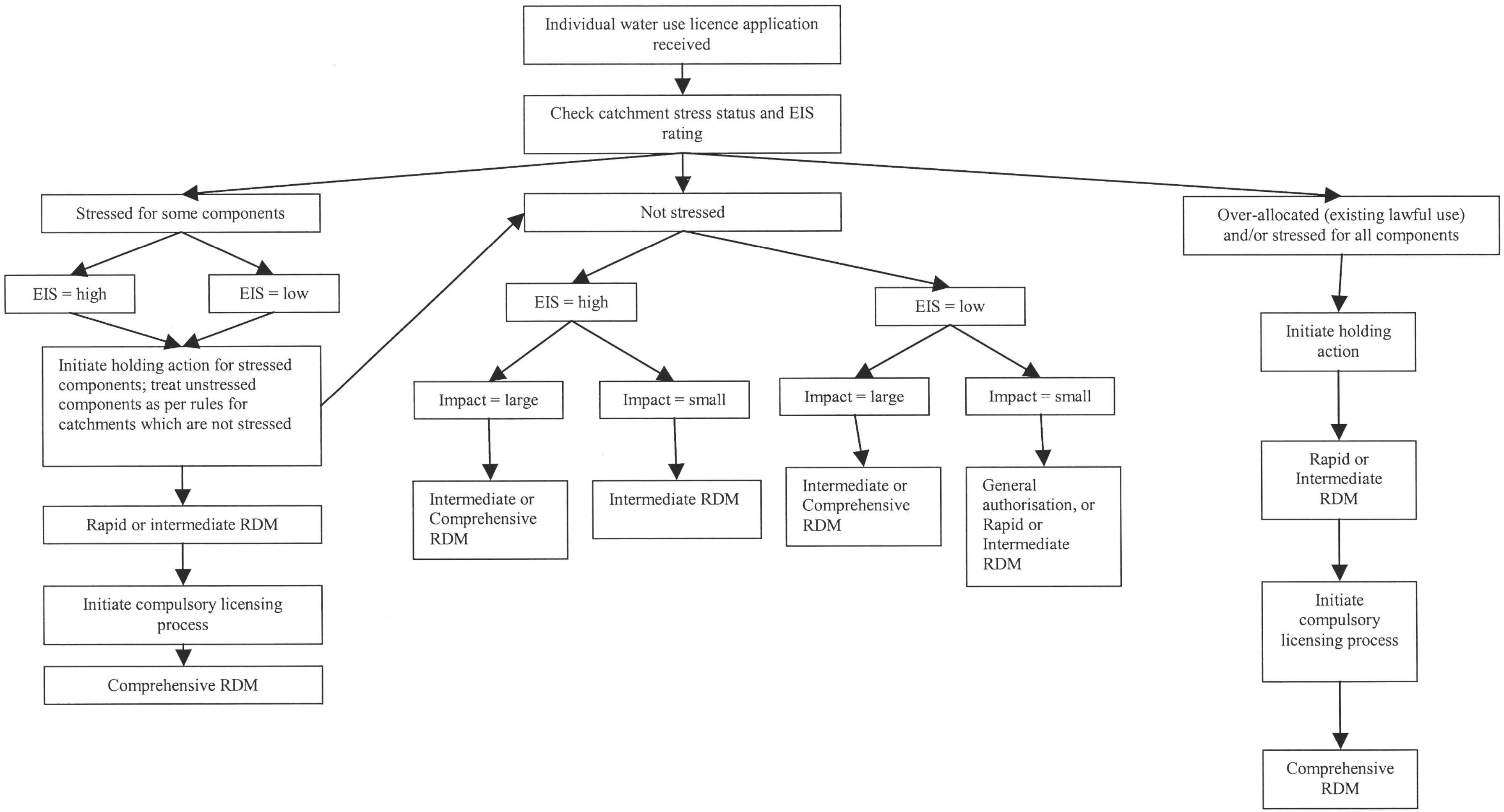

Figure 2.1 Rules for selection of level of RDM determination (DWAF, 1999a)

2.2 Instream Flow Requirements

2.2.1 Introduction

The urgent need to provide more water services often conflicts with the desire to maintain or improve the ecological condition of rivers. Modification of the natural flow regime affects both aquatic and riparian species in streams and rivers. If rivers are to be effectively and successfully managed, it is necessary to understand how the use and management of land in the catchment influences river discharge and how biota responds to changes in discharge (James 1998).

Changes in flow regimes can be characterised by five ecologically relevant variables (Richter et al, 1996; Richter, 2002):

- Magnitude of flow - the amount of water passing a fixed point in the river at a specific point in time;
- Frequency – how often a particular flow condition occurs;
- Duration – the length of time that a specific flow condition lasts;
- Timing – the time of year at which particular flow events occur;
- The rate of change of flow.

Ecological responses to altered flow regime in a specific stream or river depend on how the components of flow have changed relative to the natural flow regime for that particular stream or river, how specific geomorphologic and ecological processes will respond to this relative change (Poff & Ward 1990) and the attributes of the natural biota. Researchers in environmental flow tend to quantify the water needs of the various biotic components in terms of parameters such as water depth and flow velocity (Rowlston et al, 2000). The velocity-depth distributions and associated substrate and cover features provide a wide range of habitats for aquatic animals. Predictions of these hydraulic parameters are crucial needs in the ecological flow requirement for fish and macroinvertebrates.

Initially, the impetus of instream flow requirements studies came from western North America, where salmon fisheries of significant commercial value were threatened (Tharme, 1996; Nestler et al, 1989). As early as the late 1940s, the first study related to influence of the Granby Dam on the Colorado River on downstream condition was performed by the U.S. Fish and Wildlife Service (Tharme, 1996). The main aim of instream flow studies is to identify a quantity of water and its distribution in time and space required for maintenance of the river ecosystem. The development and application of methods and techniques for prescribing the instream flow requirements (IFRs) started in the 1950s, and since then many different types of methodologies and approaches have been proposed (King and Tharme, 1994).

2.2.2 International Methodologies and Methods

Several reviews and evaluations of these methodologies and approaches have been published (Mosley, 1983; Wesche and Rechard 1980; Stalnaker and Arnette, 1976). A comprehensive review of international methodologies for the quantification of the instream flow requirements of rivers has been conducted and published in South Africa (Tharme, 1996). In general, methodologies can be divided into four basic categories (Tharme, 2002):

1. Methodologies based on historical flow records;
2. Methodologies based on the relationship between physical habitat and discharge;
3. Methodologies based on the instream habitat simulation methods (with habitat defined in terms of the requirements of a particular target species);
4. Holistic methodologies and alternative approaches to instream flow assessment.

<u>Methodologies based on historical flow records</u>: these methods are based on hydrological data. Historical flow records are used for instream flow recommendations. The most common method of these methodologies is the Montana Method, (Tennant, 1976) which was developed in the 1970s in North America. Recommended minimum flows are based on percentages of the average annual flow, with different percentages for winter and summer months.

Other historical flow record approaches such as Hoppe, 1975 (cited in Gordon et al, 1992) and a Decision Support System (Hughes and Münster, 2000) are based on flow duration curves, and develops the relationships between recommended instream flow and the percentage of the time that it is exceeded. The main benefit of these approaches is that a rough estimation can be made if gauged records are available, alleviating the effort and necessary for field data collection for analysis.

The best application of these methodologies is to provide quick, simple, and low-confidence assessment for planning purposes. However, they are limited by the lack of any ecological interpretation of the hydrology.

Methodologies based on the relationship between physical habitat and discharge: These methods are designed to assess various conditions of physical variables in relation to fluctuations in discharge, and are primarily focused on maintenance flows for target riverine biota.

Hydraulic rating methodologies are single cross-section methods, which involve the development of relationships between discharge and other hydraulic variables, such as, wetted perimeter, water depth and velocity. One of the most often used is the Wetted Perimeter Method (Collings, 1972). The wetted perimeter method assumes that the slope breakpoint on a plot of wetted perimeter against discharge represents the quantity of water preferred by fish. The first break in slope on the curve is an indication of the optimum rearing discharge (Gordon et al, 1992). Although these methods take biota into consideration, the scale and extent of the hydraulic interpretation is very limited.

Methodologies based on the instream habitat rating or simulation: these methods combine physical habitat and habitat preferences of a given species to estimate the amount of habitat available for this species over a range of discharges.

Habitat rating methods integrate an approach referred to as Multiple Transect Analysis (Tharme, 1996). This technique involves the collection of field data at transects in a stream reach where the maintenance of flows is most critical for a target species or biological activity. Hydraulic variables are used to develop a relationship between physical habitat represented by hydraulic parameters, such as flow velocity, flow area and flow depth, and discharge.

Of all currently availably habitat simulation methodologies, Instream Flow Incremental Methodology (IFIM) and its Physical Habitat Simulation Model, PHABSIM II (Milhous et al, 1989) are the most widely used methods worldwide. IFIM was developed by the United States Fish and Wildlife Service for assisting in the assessment of instream flow requirements of rivers (Bovee, 1982). The IFIM is a problem-solving tool made up of a collection of analytical procedures and computer models. An application of IFIM consists of following steps (Tharme, 1996; King and Tharme; 1994, Gordon et al, 1992):

- Identification of the study objectives, river study reaches, and target species;
- The assessment of catchment equilibrium and macrohabitat suitability;
- Development of functions integrating macrohabitat and microhabitat availability of the present system;
- Collection of physical data, and defining physical microhabitat;
- Collection of biological data for the habitat suitability curves;
- Connection between physical and biological data using PHABSIM II;
- Hydraulic, and microhabitat simulation using PHABSIM II.

IFIM is widely used in the USA, and has been applied in Australia, New Zealand and Britain. It has been applied in South Africa for the Sabie River (Gore et al, 1992) and the Olifants River (Western Cape) (King and Tharme, 1994). Some details of the application to the Olifants River follow.

PHABSIM II is a collection of some 240-computer programs that form a major component of IFIM. It comprises two basic components: hydraulic simulation and habitat simulation. Comprehensive information of concepts and practicalities of PHABSIM II can be found in King and Tharme (1994), Tharme (1996), and PHABSIM for Windows: User’s Manual and Exercises (www.fort.usgs.gov.)

Holistic methodologies and alternative approaches to instream flow assessment: Holistic methods for the determination of ecological flow requirements quantify the flows for the various biotic components of river in terms of parameters such as flow depth, flow velocity and wetted perimeter, adding time as a parameter 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 critical flow events are identified in terms of most of the criteria defining flow variability (Tharme, 2002). The Building Block Methodology (BBM), Holistic Approach and Expert Panel Assessment Method are holistic methodologies that have been developed in the last decade (Tharme, 2002).

2.2.3 Methodologies Developed in South Africa

In South Africa, activities addressing the influence of modified flow regimes on riverine ecosystems were initiated in 1987, and the needs for the methodologies for assessing the instream flow requirements of rivers were recognised. New research in the field of instream flow requirements therefore began in 1989 (King and Tharme, 1994).

Firstly, the IFIM approach was applied in South Africa. The Olifants River (Western Cape) was chosen for learning and applying the methodology. During the study, it was found that:

- IFIM is difficult and time-consuming to learn because it incorporates concepts and skills from a wide range of disciplines;
- IFIM is difficult to apply because in places it is vague, non-pragmatic or still largely conceptual;
- PHABSIM II is complex and difficult to master, and
- At that time, the state of development of IFIM did not allow compilation of a comprehensive modified flow regime for a regulated river in the way required by South African Department of Water Affairs and Forestry.

It was concluded that IFIM is not applicable for South African river conditions, because of the exceptionally long time required to achieve a satisfactory result, its extensive requirement for quantified biological data, and difficultly in describing the low-flow hydraulics of complex river channels morphology. Consequently, development of local instream methodologies to provide guidance on the sustainable use of rivers' water-resources started in 1989 (King and Tharme, 1994).

<u>Building Block Methodology (BBM)</u>: BBM was the first method developed for assessing the environmental flow requirements (EFR) of rivers in South Africa. The conceptual basis of the BBM is that some flows within the total flow regime are more important than others for maintenance of that river ecosystem. These flows can be described in terms of their magnitude, frequency, duration and timing (King and Tharme, 1994; King, 1996; Tharme & King 1998; King and Louw, 1998). The methodology assumes the following:

- Biota associated with a river can cope with base flow conditions that naturally occur in it "often", and may be reliant on higher flow conditions that naturally occur in it at certain times;

- Identifying what are derived to be the most important components of the natural flow regime, and ensuring that they are incorporated as part of the modified flow regime, will facilitate maintenance of the natural biota and natural functioning of the river;
- Certain kinds of flow influence channel geomorphology more than other, and incorporating such flows into the modified flow regime will aid maintenance of the natural channel structure and diversity of physical biotopes.

<u>Downstream Response to Imposed Flow Transformations (DRIFT)</u>: DRIFT is a second generation methodology for instream flow assessments that was developed by Southern Waters Ecological Research and Consulting (South Africa) and SMEC International (Australia) specifically for the assessment of environmental flow for the Lesotho Highlands Water Project (King et al. in prep.).

DRIFT is an interactive, scenario-based process, which address the biophysical consequences of progressive reductions in flows and socio-economic links. The process involves a number of post data collection activities as described below:

- Preparation of the hydrological data;
- Linkage of the hydrological data to cross-sectional river features;
- Reduction of different flow components, and description of the biophysical consequences;
- Entry of the consequences into a custom-built database;
- Querying the data base to describe the changes in river condition caused by one or more potential flow regimes (scenarios);
- Identification of the social impacts of each scenario;
- Calculation of the economic cost of compensation and mitigation for each scenario;
- Calculation of the impact on system yield for each scenario.

The BBM and DRIFT are both holistic type methodologies, with three primary differences between the methods:

- DRIFT is a scenario-based interactive approach, in which a database is created that can be queried to describe the biophysical consequences of any number of potential future flow regimes. However, it does not specifically addresses the present ecological state in relation to the minimally modified system. BBM is a prescriptive approach that requires identification of a single predetermined condition in relation to the expected minimally modified condition, after which a single flow regime is described to facilitate maintenance of that condition.

- BBM "builds up" a recommended flow regime from scratch, whereas DRIFT takes the present-day flow regime as a starting point, and describes the consequences for all aspects of the river of further reducing the flow regime in different ways.

- DRIFT is designed to describe and quantify the links between changing river condition and the social and economic impacts for the riparian people who rely on the river for subsistence.

Flow-Stressor Response (FSR): FSR is a newer method designed to be used on its own or as part of holistic methods such as the BBM and DRIFT. The FSR is based on the application of a generic index describing the progressive consequences to the flow-dependent biota of flow reduction. The indices of stress range from 0 (corresponding to a condition of no stress) to 10 (very high stress stage). Flow hydraulics and associated habitat changes are related to biotic responses in terms of abundance, life stages, and persistence (O'Keeffe and Hughes, 2004).

The application of the method consists of following steps:

- Site selection, site survey, and description of sites in terms of hydraulic parameters (depth, flow velocity and wetted perimeter) at a range of discharges;
- Development of curves that describe the relationship between changing discharge and stress for critical flow-dependent species or groups;
- Converting the natural and any other flow time series to a stress time series;
- Developing stress profiles which describe the magnitude, duration and frequency of stress levels experienced by target species for different flow scenarios;
- Assessing the relative changes in biotic stress for various flow scenarios;
- Identifying the scenario for which the stress profile will impose the least additional stress to the biota.

The FSR method was used in the Thukela Project for assessing low flow focused on water quantity requirements (DWAF, 2004). The nature and altered low-flow time series were converted to stress time-series, and these in turn to stress duration curves and spell analyses.

This information was used to evaluate any provided low-flow scenario.

2.3 Ecological Flow and Hydraulics

Holistic methods for the determination of ecological flow requirements quantify the flows for the various biotic components of a river in terms of parameters such as flow depth, flow velocity and wetted perimeter, adding time as a parameter 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).

The application of holistic methods to set the ecological flows requires an interface between hydrology and other factors. This interface is found in the hydraulic analysis of flow in natural open channels. The results of hydraulic analyses and modelling therefore form the essential link between the way in which the hydrologists, engineers and water managers express the flow of water in the river in terms of flow rate, and the way in which river ecologists express the water requirements of the river ecosystem itself in terms of depth, velocity, etc. (Birkhead, 2002).

Application of BBM, DRIFT and FSR require that flow requirements for geomorphological, ecological and river dependent social needs are expressed as volumetric flow rates. The success and confidence with which flow requirements are assessed depends to a large extent on the quality and reliability of the hydraulic information. Approaches have been developed for the application of river hydraulics in EFR assessment based on collaboration with specialists, including hydrologists, fluvial geomorphologists, and riparian vegetation, fish and invertebrate biologists (Rowlston et al, 2000). These approaches are discussed with reference to the location of appropriate sites for environmental flow assessment, topographical river channel surveys, requirements for the collection of hydraulic data, appropriate hydraulic analysis and modelling, and the presentation of hydraulic information for use by specialists assessing the environmental flow requirements during EFR specialist meeting.

The Terms of Reference for the hydraulic specialist in the descriptions of the tasks necessary to carry out the study as in the Manual for the Building Block Methodology (King et al, 2000) are:

- Site selection;
- Sites cross-sectional and longitudinal profiles surveys;
- Collection of hydraulic data;
- Reduction of survey and hydraulic data;
- Hydraulic analysis and modelling;
- Reporting;
- EFR specialist meeting.

The responsibility of the hydraulic specialist is to carry out hydraulic analysis and modelling, to provide hydraulic information to assist aquatic scientists in determining ecological flow requirements. The hydraulic parameters such as flow velocity, flow depth and depth distribution for a given discharge have to be developed with the highest possible level of confidence.

Over the last ten years more than 50 environmental flow requirements studies with application of BBM as well as DRIFT and FSR have been carried out in South Africa. The experience with the determination of ecological flow requirements has repeatedly shown that the availability of reliable hydraulic information is of quintessential importance to the success of the process as a whole.

2.3.1 Ecological Reserve Determination

There are four levels of RDM determination:

- Desktop;
- Rapid;
- Intermediate;
- Comprehensive.

The desktop determination is a quick, often very low confidence assessment proposed for use in the National Water Balance Model. For the desktop estimation a local desktop reserve model is used for an initial low confidence estimate of the quantity component of the Reserve for rivers was therefore developed (Hughes and Hannart, 2003). The rapid determination is a low confidence estimation using the desktop model with quick field assessment of present ecological status, proposed for use in unstressed catchments of low ecological importance and sensitivity. The intermediate determination is a medium confidence assessment. It is a team field study proposed for use in relatively unstressed catchments. A higher level of confidence is provided by the comprehensive assessment, where extensive field data should be collected and used by specialists for the quantification of the Reserve. The approach is proposed to be applied for very ecologically important and/or sensitive catchments (the size of the river/reach as well as the type and extent of water resource development are important considerations.)

To quantify the ecological Reserve of any water resource, the amount of water needed for aquatic ecosystem maintenance should be determined. Physical habitat of aquatic animals can be approximately described by hydraulic variables such as the flow depth, flow area, wetted perimeter and flow velocities. The primary product of hydraulic work comprises a series of relationships between flow rates and flow depth, flow velocity, wetted perimeter and water surface width. Fluvial geomorphologists and ecologists use this information to make flow recommendations. Hydraulic analysis and modelling therefore form the essential link between aquatic habitats and flow requirements.

The principles required to provide hydraulic information for different Reserve estimations are the same, regardless of the level. The difference between rapid, intermediate and comprehensive assessment lies in the amount of measured hydraulic data, and therefore in the accuracy of and confidence in the results produced. It is clear that greater confidence is expected for higher levels of determination (Birkhead, 2002).

Discussion of the procedures for generating hydraulic information for the different levels of Reserve determinations is presented in the next section.

2.3.1.1 Rapid Determination

The rapid level is a comparatively low confidence determination, but includes one field observation and data collection trip. The site selection team normally includes only a hydraulician and some specialists, who represent the site-specific needs of the various ecological components. During the trip, hydraulic data required for the hydraulic modelling should be measured. This includes a cross-sectional survey of selected IFR sites, a survey of the longitudinal slope of the water surface and a measurement of discharge. The responsibility of the hydraulics-related details of the survey lies only with the hydraulician and the ecologists from the team. The field trip should take a place during low flow conditions.

Based on the one set of observed rating data, the hydraulician involved in the rapid determination should have sufficient expertise to carry out the hydraulic modelling on-site.

2.3.1.2 Intermediate Determination

A task flow sequence diagram for the Intermediate Reserve determination, based on the generic RDM procedure, is shown in Figure 2.2. According to the Terms of Reference (King et al, 2000) the hydraulician's involvement should start at Task IV, when the selection of IFR sites is expected to take a place. The site selection team has to be adept with the detailed method for selecting IFR sites. At each selected site the cross-section should be correctly placed from both hydraulic and biological perspectives. The survey of the cross-sectional profile of the river channel has to be undertaken at the level detail required for the intermediate determination (Birkhead, 2002).

In order to develop stage-discharge relationships, two to three observations over a range of flows are expected. When observed rating data exist, hydraulic modelling of rating relationship for flows higher and lower than the observed is required (Figure 2.3). The next step is to fit recorded and modelled rating data to relationship of the form given by Birkhead and James (1998)

$$y = aQ^b + c \qquad 2.1$$

where y is the maximum flow depth (m), Q is the discharge rate (m^3/s), and a, b and c are regression coefficients.

Once the rating relationship developed, it is can be converted into relationships between flow rate and the biologically useful hydraulic parameters such as velocity, flow area and wetted perimeter (Figure 2.4).

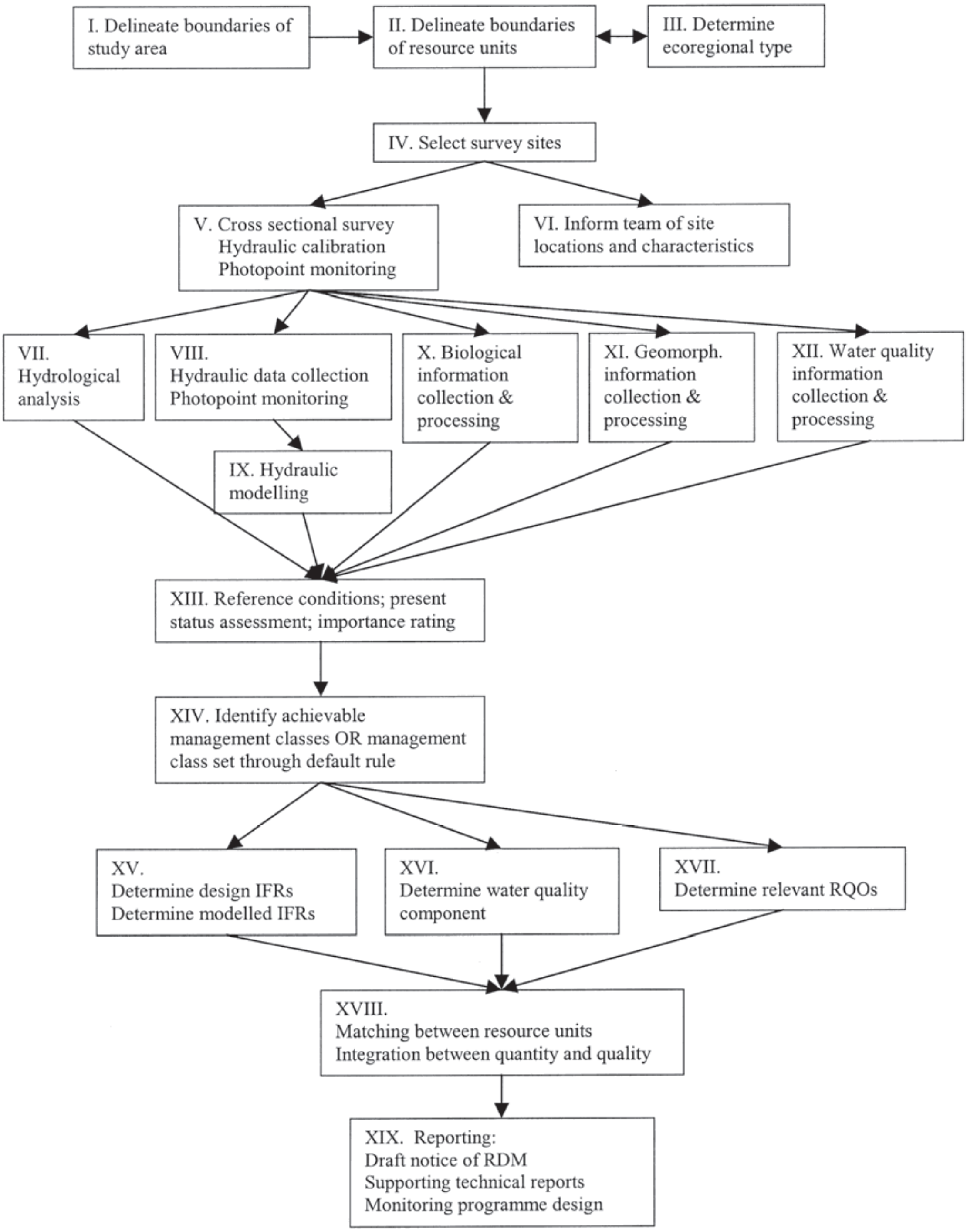

Figure 2.2 **Task flow for intermediate RDM determination (DWAF, 1999a)**

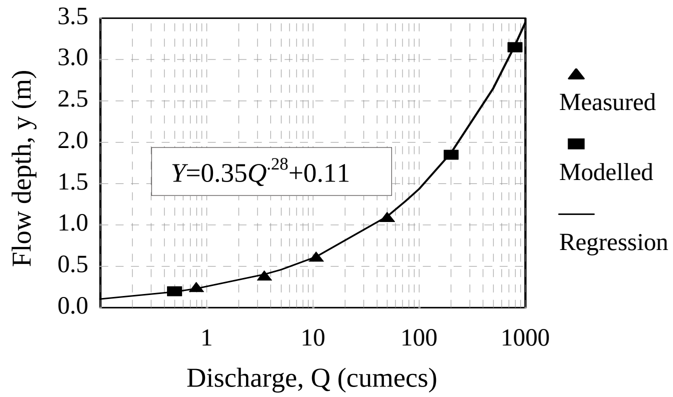

Figure 2.3 **Example plot of a rating relationship on semi-log scale showing the observed and modelled data.**

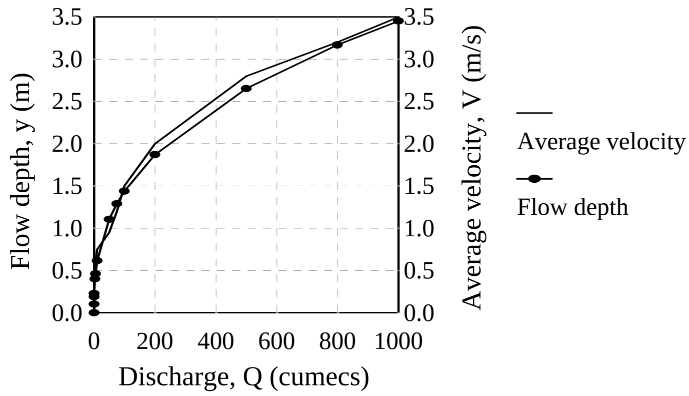

Figure 2.4 **Example plots of discharge against average velocity and flow depth on normal scale axes.**

2.3.1.3 Comprehensive Determination

The approach for Comprehensive Reserve determination follows that described for the rapid and the intermediate determinations, with these differences:

- the survey of selected EFR sites should include all details required by the ecologist of the team, such as the position of plants on the cross section and all geomorphological features;

- in order to observe as wide a range of discharge as possible, the measurements of discharge and related stage should be undertaken over at least one hydrological season;
- 4 to 5 observations of discharge and stage over a range of flows are required;
- habitat hydraulic modelling at key EFR sites is expected;
- the survey of key EFR sites should include all topographical details, including substrate as well as the position of plants on the cross section and the inclusion of various velocity and depth classes (eg. riffles, backwaters, overhanging vegetation);
- the results should provide a relatively high degree of confidence.

2.4 Conclusions

Ecological Reserve determination is an estimation of the flow requirements of different components of a river. It focuses on the amount of water required to maintain the system in a particular ecological condition. As habitats for different life history stages of aquatic animals are related to hydraulic parameters such as flow velocity and flow depth, it is required that the amount of water should be converted into such parameters. Hydraulic analyses are the key link in the ecological flow determination. Furthermore, there are three levels of the Reserve determination, and this necessitates implementation of the hydraulic analyses at each level.

In order to be successful in the determination of the ecological Reserve for the rivers in South Africa, it is important to have a full understanding of the current process related to the water resources protection. The understanding of the ecological flow requirements of river ecosystems, and the application of appropriate hydraulic methods are inalienable parts of the whole process.

Chapter 3

THE NATURE OF HYDRAULIC PARAMETERS AND THEIR RELATIONSHIP TO BIOLOGICAL HABITAT

3.1 Introduction

A growing need to provide more water services often conflicts with the desire to maintain or improve the ecological condition of the rivers for biodiversity and conservation goals. Modification of the natural flow regime affects both aquatic and riparian biota in streams and rivers. Ecological responses to the altered flow regime in a specific stream or river depend on how the components of flow have changed relative to the natural flow regime for that particular stream or river (Poff & Ward 1990), and how specific geomorphologic and ecological processes will respond to this relative change.

Impacts of modified flow on river biota have been reported widely (see for example Ward and Stanford, 1979, Cushman, 1985, Moog, 1993, and Ward and Stanford, 1995). Predictive capability regarding ecological impacts of human activities on ecological sustainability is a key factor in water management activities. Water resource management goals that sustain river ecology and socially and economically valuable goods and services are, therefore, a prime area of research and management (Richter et al, 1997). River management objectives related to ecosystem integrity cannot be met without maintaining a particular level of hydrological integrity. Flow is strongly correlated with the most important physicochemical factors in an ecosystem, which in turn, influence species richness, population dynamics, resilience and abundance (Poff and Ward, 1990). For effective and ecologically responsible river management, an understanding of aquatic habitats and links with the physical hydraulic parameters in rivers, such as flow depth, flow velocity and substrate is essential.

3.2 Hydraulic Habitat for Fish

Rivers and streams are flowing ecosystems, which function through the creation and maintenance of habitats for aquatic biota. Habitats for fish are defined as “places where individuals, populations, or assemblages can find the physical and chemical features needed for life. Habitat features include water quality, spawning sites, feeding areas, and migration routes" (Bain and Stevenson, 1999). Fish live, therefore, in a wide range of stream flow conditions that depend on hydraulic determinants such as flow depth and velocity, and that vary spatially and temporally.

3.2.1 River Structural Characteristics and Fish Habitat Preferences

Fish experience upstream-downstream gradients in natural environmental variability. Such patterns of upstream-downstream environmental variation, and the consequent adaptations of life history characteristics are reflected in the temporal variation in community structure of fish (Schlosser, 1990). Environmental conditions of the upstream and downstream areas are associated with changes in flow regime, channel morphology, and physical-chemical attributes such as temperature and oxygen. These longitudinal environmental changes affect life history characteristics. Generally, upstream species have a shorter life-span, smaller maximum body size, and earlier sexual maturity than downstream species. Furthermore, upstream fish exhibit more rapid recolonization and recovery from severe disturbances than downstream fish communities. There are basic differences in temporal variability of fish assemblage structure along streams. Climatic variations, such as harsh winter conditions and fluctuations in stream flow result in a temporally variable fish assemblage structure in upstream areas, and in a relatively stable fish community structure in downstream areas. The general pattern of adaptation follows the river continuum concept (Vannote, et al 1980) and the associated life-history strategies.

Generally, structural characteristics of stream reaches consist of sequences of habitat channel units such as pools and riffles (Bisson, et al 1982). Classification of fluvial hydraulics, which affects fish populations and fish assemblages, were described for low-gradient streams in the Ozark Plateau region of the central United States (Rabeni and Jacobson, 1993).

Hydraulic units were identified as:

1. Pools
    - Bluff
    - Lateral

- Obstruction
- Mid-channel
- Forewater
- Backwater
- Edgewater

2. Runs
3. Riffles
   - High-gradient
   - Medium-gradient
   - Low-gradient

Detailed studies (Probst et al, 1984, Todd and Rabeni, 1989, and Livingston and Rabeni, 1991) on habitats of two fish species with different requirements, smallmouth bass and northern hog sucker, were used to generalize the link between physical and biological habitats. It was found that fish have affinities for particular habitat units, which differ between species, and by time of day and season.

However, the channel unit scale of resolution is not sufficient to describe habitat preferences for fish. For this reason, in each channel habitat unit, habitat at a smaller scale can be classified in different ways, which reflect the importance of variables such as flow depth, current velocity, current variability, substrate coarseness, and substrate heterogeneity.

One method is to classify habitat in terms of subunits such as midstream of riffles (MR), pool tail (PT), pool head (PH), fast-current edge (FE), and slow-current edge (SE) (Inoue and Nunokawa, 2002). Longitudinal variations of these hydraulic variables were shown to have an effect on the abundance of masu salmon (*Oncorhynchus masou*) and rosyface dace (*Leuciscus ezoe*). Habitat preferences for each subunit type can be estimated by Manly's Index (Chesson, 1978):

$$\alpha_i = \frac{r_i / n_i}{\sum_{j=1}^{m} r_j / n_j} \qquad 3.1$$

in which α_i is the preference value for an i^{th} subunit type (of m types) at a particular site, and r_i and n_i are the proportions of the i^{th} subunit type in cells used by fish in all cells within the site respectively where i=1, 2, m. Both species, masu salmon and rosyface dace, used pools as a major habitat, but masu salmon preferred a subunit type occurring at pool heads while the rosyface dace preferred slow-current edge type conditions. Longitudinal variations in the abundance of both species are related to the abundance of subunit habitat rather than channel-unit habitat.

Movement between aquatic habitats is essential in the life of many stream fish due to the requirements of different life-history stages. Many stream fish occur in pool habitats, and inter-pool movement is therefore critical to promote exchanges among habitat patches in streams (Schlosser, 1995). In this context, the effect of riffles as barriers to the movement of fish between pools is essential (Schaefer, 2001). The riffle lengths and current velocity significantly influence movement rate of fish with a predominant preference for pools (*Notropis boops, Campostoma anomalum* and *Cyprinella venusta*). The movement rate across the riffle decreases with increasing the riffle length and the riffle current velocity.

3.2.2 Flow Characteristics and Fish Habitat Preferences

In addition to the physical characteristics discussed above, temporal flow velocity variability is a primary determinant in the management of fish stocks. Correct determination of flow velocity patterns relates to an accurate prediction of erosion and sedimentation of the stream bed and thus the success of spawning activity (Beebe, 1996). An investigation on how the flow velocity pattern changes with an increasing mean flow velocity and/or with mean flow depth was performed based on field data collected from salmon spawning streams in Ontario, Canada. Velocity data were obtained at 35 stations on three rivers in southern Ontario. Velocities were measured at 0.2, 0.4, 0.6, 0.8, and 0.95 of the flow depth, and were used to create topographic and three-dimensional, x-y-z, surfaces of flow velocity. Such full data plots were compared with plots of velocity profiles measured at 0.6 of the flow depth. The results showed that flow measurement taken from the common reference of 0.6 of the depth produced larger errors in velocity predictions near the bed and stream surface. Errors in the predictions of near-bed flow velocities could result in the entrainment of particles within the preferred spawning range of salmonids. This points to the importance of collecting all relevant data before implementing management decisions.

Fish habitat preferences in six large streams in southern France were related to three habitat variables, water velocity, depth and dominant particle size (Lamouroux et al, 1999a). A local log-density (*LLD*) for each of studied species and their size classes were calculated as:

$$LLD = \ln\,(1+1000d) \qquad 3.2$$

where *d* is the areal density of the species (the abundance divided by the plan area of the habitat unit). Analysis of data confirmed that most species and size classes of fish have strong preferences for local velocities, depths or dominant roughness.

Habitat preferences of fish for both structural and flow characterictics are different for different life history stages. In order to related habitat preference to a specific group, three functional groups of the rock catfish (*Austroglanis sclateri*) as recruits, juveniles, and adults were studed in the Senqunyane River, Lesotho (Niehaus et al, 1997).

Habitat preferences of recruits are related to backwater pools while the juveniles and the adults preferred stickles and runs respectively. All functional groups preferred rubble bottom substrate. Mean preferred flow depths for the recruits and the juveniles are similar, 20 and 26.5 cm respectively, while the adults preferred deeper water depth (58.6 cm). Mean preferred velocity for the recruits is smaller than 0.1 m s^{-1}. Juveniles are preferred velocities of 0.4 while adults preferred velocity is 0.5 m s^{-1}.

3.2.2.1 Depth-Velocity Classes

Prediction of instream fish habitats requires an understanding of the relation between the fish and physical habitats. Fish habitats can be categorisd into four flow-depth classes (Oswood and Barber, 1982, as adapted by Kleynhans, 1999):

- Slow-deep (SD): depth > 0.5m, and velocity < 0.3 m/s. This includes deep pools and backwaters,

- Slow-shallow (SS): depth < 0.5 m, and velocity < 0.3 m/s. This includes shallow pools and backwaters,
- Fast-deep (FD): depth > 0.3 m, and velocity > 0.3 m/s. Deep runs, rapids and riffles fall in this category, and
- Fast-shallow (FS): depth < 0.3m, and velocity > 0.3 m/s. Shallow runs, rapids and riffles fall in this category.

For each flow-depth/velocity class, the following fish cover types have to be considered (Kleynhans, 1999):

- Overhanging vegetation
- Undercut banks and root wads
- Stream substrate
- Aquatic macrophytes
- Water column.

3.2.3 Prediction of Fish Habitat Suitability

Stream hydraulics and direct and indirect response variables such as food, temperature and geomorphology have a strong impact on fish assemblage attributes. To facilitate the prediction of fish assemblage characteristics, it is necessary to identify key processes at the local scale, which are relevant over larger scales (Lamouroux et al 1999b). Lamouroux et al (1998) proposed a method for estimation of habitat suitability as a function of discharge by linking statistical hydraulic models with multivariate habitat use models. The method was applied to a regulated reach of the French Rhone River. The method, focusing on predictions of the structure of river fish assemblages based on the characteristics of the physical habitat template, was designed in five steps:

- Describing a statistical habitat model,
- Applying the model to predict assemblage characteristics in eleven river reaches,
- Validating predictions using data from long-term fish databases,
- Establishing links between the fish assemblage and hydraulics, and

- Explaining the impacts of impoundment on fish assemblage characteristics.

Three of the eleven reaches were used as the basis of habitat model development. The model was applied to predict community characteristics in eleven reaches. The predictions were compared with observations using a large fish data set that was accumulated over an extensive period of time. This showed that it is possible to predict fish assemblage characteristics from fluvial hydraulics.

Another development involved using hydraulic parameters to link average and recommended discharge values. A method developed for preliminary recommendations of minimum instream flows for the protection of aquatic life in Virginia was proposed by Orth and Leonard (1990). The proposed method uses hydrological data, based on the average discharge calculated for each season. Analysis of the habitat preference of fish was accomplished by applying the Physical Habitat Simulation System (PHABSIM, Bovee, 1982). Two approaches, commonly used in North America for general in-stream flow requirement assessments, the Tennant (1976) and the Aquatic Base Flow (US Fish and Wildlife Service, 1981) methods were applied to compare recommended flows. Four sites in the upper James River basin of Virginia and nine target species were selected for this purpose. At each study site six to eight transects at hydraulic controls and over major habitat types were established. Flow recommendations, based on species life history and preference of various life stages were developed for four seasons:

- December-March: winter non-spawning
- April-May: early spawning
- June-July: late spawning
- August-November: summer-fall non-spawning.

An assumption was made that optimum flows provided the best possible combination of habitat conditions for all species considered. The optimum recommended flow derived from average discharge (*AD*; m^3s^{-1}) for any season was proposed as:

$$Q_{opt} = 0.583AD^{0.746} \tag{3.3}$$

Flow recommendations to maintain habitat at 40, 60, and 80 per cent of the optimum flow as a function of the average discharge were proposed as well:

$$\begin{aligned} Q_{80} &= 0.418AD^{0.746} \\ Q_{60} &= 0.327AD^{0.746} \\ Q_{40} &= 0.246AD^{0.746} \end{aligned} \qquad 3.4$$

This method provides water resource managers of Virginia with an alternative way of recommending flows based on a range of possible fish habitat maintenance objectives.

A similar approach was adopted for recommending minimum desirable streamflow (MDS) values for selected streams in Kansas. The approach is based on a modified habitat evaluation procedure (HEP) (Layher and Brunson, 1992). A standard policy of recommending minimum desirable streamflow (MDS) values that support 80% of the average fish habitat units (HU) available at median discharge was used. Existing data on fish populations from 420 streams, and long term hydrological records from permanent gauging stations operated by the US Geological Survey, were used for the development of the modified HEP. Eight reaches on four streams were selected for study purposes. Historical hydrology data (Burns, 1971) were used for determination of mean depths, mean velocities, and mean widths at each cross section. The year was divided into two periods:

- A spawning period (April to June), and
- A maintenance period (July to March).

For each period monthly median flows were calculated and habitat suitability curves developed according to techniques described by Layher and Maughan (1985) to derive the total fish standing crop, mean depth, mean width, and mean velocity. These values were converted to habitat suitability indices (HSI), and were then used for estimation of fish habitat units (HU) at different discharges.

3.3 Hydraulic Habitat for Macroinvertebrates

3.3.1 Ecological Effect of Flow Regulation – General

A number of studies were conducted on the ecological effects of flow regulations on river biota (eg., Armitage et al, 1987, Gore et al 1989, Morgan et al, 1991, Petts et al, 1993, Finlayson et al, 1994, Englund and Malmqvist, 1996, Ward and Stanford, 1997, Growns and Growns, 2001, Cortes et al, 2002). The influence of flow in regulated rivers on river biota and fauna can be interpreted through the physical response of the rivers to modified flow, which affects the aquatic habitats. There are four possible ways (Ward and Stanford, 1997) in which modified flow may impact on streams:

- Reduced flow will cause decreased local flow velocity, decreased stream habitat, and increased stream bed siltation.
- Seasonally constant flow cause uniform flow velocity, which can enhance stability of aquatic and riparian vegetation.
- Increased flow cause increased local flow velocity, which may result in a change of the stream substratum.
- Short-term flushing can cause velocity and depth fluctuations, turbulence, and bed and bank instability.

3.3.2 Important Components: Substrate and Velocity

Riverbed substrate elements are important in the creation of suitable habitat for macroinvertebrates. The biological relevance of a near-bed flow regime has not been formally established and the terms 'pool', 'run' and 'riffle' are not always useful for differentiating between habitat conditions in the near-bed zone (Young, 1993). Near-bed flows can be described by combining flow velocity, flow depth and substrate roughness to provide a means of quantifying the flow regime occurring within the microhabitats of stream benthos (Davis and Barmuta, 1989, Young, 1992, and Young, 1993).

As for fish, different methods of description or categorization of macroinvertebrate habitats have been proposed.

3.3.3 Depth, Velocity and Microprofile

Gore (1978) studied the relationship between current velocity, flow depth, and the benthic macroinvertebrates in the Tongue River. A total of 225 benthic samples were taken at various riffles along the river. For each sample, depth, flow velocity and microprofile were measured, and Froude numbers were calculated. A special device was used to survey and to describe a bed roughness. A single descriptive microprofile index (MI) of bed roughness was devised for habitat diversity description. A minimum flow recommendation method based on an assumption that species diversity and/or the number of individuals of a particular species are highest at optimum flow conditions, was proposed. Centroids for optimum flow depth conditions and current velocity for the common macroinvertebrates of the Tongue River were calculated as:

$$C_v = -\frac{\sum vH}{\sum H} \qquad 3.5$$

$$C_d = \frac{\sum dH}{\sum H} \qquad 3.6$$

where C_v is the centroid for diversity and current velocity (v), C_d is the centroid for diversity and flow depth (d), and H is diversity, which calculated as:

$$H = -\sum p_i \ln p_i \qquad 3.7$$

Where p_i is the proportion of the i^{th} species of S species within the sample. It was found that conditions of highest diversity were present where current velocities ranged from 0.75 to 1.25 m/s at a flow depth of 0.20 to 0.40 m. The optimum condition was found to occur over medium sized cobble substrates at a flow depth of 0.28 m and current velocity of 0.76 m/s.
Davis and Barmuta (1989) used the pipe flow research conducted by Morris (1955), and proposed an approach to identify different near-bed flows in rivers and streams.

Two main aspects of flow relevant to benthos were recognized:

- the mean motion of the water and the habitat diversity near the stream bed, and

- the influence of the substrate configuration on flow patterns and velocity in the near-bed region.

3.3.4 Near-Bed Flow Categories

Davies and Barmuta (1989) used physical factors (flow depth, D, roughness height, k, longitudinal spacing, λ "groove" width, j, and roughness density, N) to explain the distribution and abundance of stream benthos, and five categories of near-bed flows were recognized:

- hydraulically smooth
- hydraulically rough - chaotic flow
- hydraulically rough - isolated roughness flow
- hydraulically rough - wake interference flow, and
- hydraulically rough - skimming flow.

The longitudinal spacing, λ between substrate elements was identified as the dimension of greatest importance in determining the nature of the flow microenvironment. If the roughness elements are far apart and the wake zone and vortex zone at each element are completely developed then the isolated roughness flow will occur. For this type of flow the roughness index λ/k was identified to be a significant parameter. When the roughness elements are placed close together and the wake and vortex zones at each element are not completely developed a flow named wake interference will occur. The ratio of y/k (y is the depth of water above the roughness elements) was indicated as an important parameter in determining the presence of the wake interference flow. Skimming flow occurs when the roughness elements are so close together that the flow skims the tops of the elements. For skimming flow the roughness index λ/k is more important as a hydraulic parameter (Morris, 1955).

In addition to determining the dimensions which exhibit the major influence on each flow category, a method was also needed to distinguish which flow category would occur. Morris (1955) derived an equation for calculation of the critical value of the longitudinal spacing, λ which separated two flow categories - isolated roughness and wake interference

$$\frac{\lambda/k}{C_D\left(1-ns/P\right)}=\frac{67.2}{\dfrac{100}{\left(2\log\left(y/\lambda\right)+1.75\right)^2}-1} \qquad 3.8$$

where C_D is the roughness element drag coefficient, n is the number of elements across a section, s is the cross-stream groove width, and P is the cross-stream wetted perimeter. A similar criterion for differentiating between wake interference flow and skimming flow was not found.

Young (1992) simplified the Morris (1955) equation (3.8) and derived an equation for prediction of the threshold between wake interference and isolated roughness flows

$$\lambda_{crit}=2.46k\left(y/k\right)^{0.42} \qquad 3.9$$

A simplification of this was based on assumptions that a value of C_D (1-ns / P) is constant, and the roughness elements are long and flat.

As was mentioned, the threshold between wake interference flow and skimming flow is physically not so well defined as the threshold between wake interference and isolated roughness flows. Young (1992) explained a physical difference of wake interference and skimming flows as a relation of the roughness height and groove width. He suggested that if $j \leq k$ the skimming flow will occur, and for $j >> k$ the wake interference flow will occur. For streambed roughness elements a value of j/k = 1 (k is the roughness height, and j is the "groove" width) was suggested as the threshold between wake interference and skimming flows.

For better understanding the near-bed flow structure a section of selected field site of the cobble bedded Taggerty River in south-eastern Australia was reconstructed in a laboratory flume (Young, 1992). Extensive measurements of near-bed flow velocity were performed by a laser-Doppler, and qualitative descriptions of the flow that occurred, were reported. During the experiments, velocities that were observed characterized all different types of flows. The importance of flow hydraulics suggests that more detailed measurements of hydraulic variables in stream ecology studies should be taken to ascertain the importance of all four near-bed flows in the quantification of the availability of different habitat types.

Young (1993) proposed field techniques for the identification of near-bed flow regimes. The methods have been tested in the Acheron River, south-eastern Australia. Four sites were selected. At each site, bed roughness profiles and flow depths as well as three axis dimensions of a random sample of the stream bed surface were measured at selected subsites. A criterion for the selection of the subsites was to sample a number of runs, pools and riffles often used by stream ecologists as a basis for habitat differentiation. A mean roughness height, k, a mean roughness spacing, λ, and mean groove width, j, were calculated. Using the Young (1992) criteria, observed near-bed flow regimes were classified. It was found that habitat classification on the basis of near-bed flow regime might be more appropriate for stream ecologists in studies of macroinvertebrates than habitat classification in terms of 'pool', 'run' and 'riffle'.

3.3.5 Flow Zones

Each of the near-bed flow regimes has a number of different flow zones where velocities are different. Flow velocity is an important hydraulic parameter that relates to the physical habitat of benthic invertebrates. From an analysis of near-bed flow velocities measured in a reconstruction of a cobble river bed in a flume, four hydraulically different habitats have been identified (Young, 1996):

- the exposed tops of roughness elements (TOPS)
- the sheltered lees of roughness elements (LEES)
- the exposed faces of roughness elements (FACE)
- the partly sheltered areas mid-way between roughness elements (MIDS).

The flow zones have been suggested as more relevant to the prediction of benthos distribution than habitat classification in terms pools, runs and riffles. These habitat elements are independent of flow classified by Davis and Barmuta (1989) as skimming, wake interference, isolated roughness and chaotic flow regimes.

The differences in flow velocities between the four hydraulic habitat types were determined by Young (1996). Analysis of these measurements showed that both sheltered and exposed hydraulic elements exist in the near-bed and that there are significant differences between the four hydraulic habitat elements. The average velocities were 1.7 % and 14 % of the mean mainstream velocity in the sheltered habitat and in the partly sheltered habitat types respectively. This study shows that mean stream velocity does not characterize the habitat diversity of different roughness elements in cobble bed streams sufficiently for effective ecological interpretation and prediction. Benthic flow conditions are very complex, and the mean flow velocity and the mean flow depth are not considered useful in ecological studies (Statzner et al, 1988).

3.3.6 Important Components: Substrate and Velocity Continued

Comprehensive field measurements of near-bed velocities at the spatial and temporal scales are used to characterize the environment in which macroinvertebrates live (Hart et al, 1996). Using hot-film anemometry spatial variations in current velocity for heights between 1 and 10 mm above the bed were measured. Average velocities measured 2 mm above the bed ranged between 0.07 and 0.59 m/s. The results revealed highly complicated flow variations in both space and time, and that these determine the complex ecological patterns of benthic stream environments.

Velocities around boulders under natural field conditions can now be measured with the aid of highly developed instruments such as acoustic Doppler velocitimeter (ADV). The ADV can be used to measure velocity at fine-scale for a given point of interest as well to estimate turbulence intensity and shear stress. Field velocities measurements around boulders are showed the complex flow patterns especially when a large roughness element is predominated in determining the flow configuration (Bouckaert and Davis, 1998). Near-bed velocities measured at the front and wake regions didn’t show significant different while the benthos differed significantly between these regions. This suggested that benthic macroinvertebrate communities may be influenced by turbulent regimes rather than directly by velocities and associated drag forces.

3.3.7 Ecological Effect of Flow Regulation on Macroinvertebrates

Ecological effects of flow regulation on aquatic macroinvertebrates and periphytic diatoms were studied in the Hawkesbure-Nepean River, Australia (Growns and Growns, 2001). The aim of the study was to demonstrate the effects of six dams and two weirs on diatom flora and macroinvertebrate fauna. Study sites were selected to demonstrate the effects of the dams and the weirs as well as the impact of two forms of flow modification caused by a water supply system (reservoirs and off-take weirs). Selected sites were situated at regulated and unregulated reaches. The regulated sites were divided into two groups, those that received water releases, and those that did not receive any water releases from the reservoirs during the study.

Macroinvertebrates were sampled at each site in three habitat feature combinations:

- Stream bed in fast flowing water (riffles),
- Stream edges in still water (edge), and
- Rocks in slow flowing water (pool-rock).

Hydrological variables were calculated from a six-month mean daily discharge as:

- Baseflow index (lowest daily discharge / mean daily discharge x 100),
- Coefficient of variation (standard deviation of daily discharge / mean daily discharge x 100),
- Median daily discharge,
- Maximum daily discharge,
- Minimum daily discharge,
- Median daily discharge difference,
- Number of days with no discharge,
- Flood duration, and
- Flood frequency.

Similarity analysis was applied to these variables to examine differences in community structure of each biotic group between each of the site groups i.e. unregulated, sites with water releases and sites with no water releases. The results of the analysis showed that the number of macroinvertebrate species was significantly lower at regulated sites than at unregulated sites. In addition, riffle and pool-rock macroinvertebrate assemblages differed between the two types of flow regulation. This suggests that local hydraulics, flow depths and flow velocities, have a significant effect on aquatic macroinvertebrates.

3.4 Conclusion

An ecological Reserve determination requires estimation of instream flow, which will maintain the aquatic habitats. The link between the aquatic habitats and the stream flow has to be found through hydraulic modelling. As the main aim of this project is improvement of the hydraulics presently used in the Reserve determination, a literature survey has been carried out to investigate the relationship between aquatic habitat and hydraulic parameters.

It is clear that the diversity of aquatic habitat depends on instream flow characteristics as well as river substratum roughness. Furthermore aquatic habitats required for different life-history stages can be determined by flow velocity and flow depth. However average depth and velocity cannot describe the diversity of cross-sectional hydraulic parameters. Modelling of cross-sectional velocity and depth distribution for a given discharge is therefore required for recommending ecological flows for fish and macroinvertebrates.

Hydraulic habitat for macroinvertebrates is related to a near-bed flow regime determined by the substrate configuration and its influence on flow patterns and velocity in the near bed region. There are a number of different flow zones where velocities are different (Young, 1996). It was suggested that benthic macroinvertebrate communities may be influenced by turbulence rather than directly by velocities and associated drag forces (Bouckaert and Davis, 1998). In this connection future research related to the near-bed flow is suggested.

Chapter 4

HYDRAULICS UNDER CONDITIONS OF LARGE-SCALE ROUGHNESS

4.1 Introduction

Hydraulic analyses required to assist in determination of the ecological Reserve are related to low flow conditions. Hydraulics under low flow (where the flow depth and the height of the substrate elements are of the same order of magnitude) is known as conditions of large-scale roughness. Successful prediction of flow resistance of the large-scale roughness depends on general understanding of the nature of the flow resistance, and application of the appropriate approaches for its prediction. Open channel flow resistance and approaches that have been developed internationally for predicting flow resistance under different conditions governed by roughness scales are discussed below.

4.2 Open Channel Flow Resistance

Flow resistance describes a process in river streams by which the physical shape and bed roughness of the channel control the depth, width and mean velocity of flow in the stream. Theoretical aspects of open channel flow resistance are documented in some publications such as Leopold et al (1960), Rouse (1965), Bathurst (1982), and Yen (2002). The flow resistance in an open channel has four contributing components (Yen, 2002):

- Skin friction,
- Form resistance,
- Wave resistance, and
- Flow unsteadiness.

Skin friction resistance depends on the roughness of the surface material, and influences the near surface flow. Form resistance is caused by flow separation and secondary circulation. Wave resistance depends on distortions of the free surface. Flow unsteadiness is associated with longitudinal flow accelerations and decelerations.

Prediction of flow resistance in natural open channels is a complex task because of all the different sources of resistance. Some publications such as "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains" (US Geological Survey, 1989) describe procedures for determining the flow resistance in natural open channels using the Manning equation (4.7). According to US Geological Survey (1989) the value of n for natural channels and flood plains can be calculated as

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \qquad 4.1$$

where n : Manning resistance coefficient,

n_b : basic value of n for a straight, uniform, smooth channel in natural materials,

n_1 : correction factor for the effect of surface irregularities,

n_2 : value of variations in shape and size of the channel cross section,

n_3 : value for obstructions,

n_4 : value for vegetation and flow conditions, and

m : correction factor for meandering of the channel.

Successful prediction of flow resistance depends on an understanding of flow resistance phenomena as well as application of an appropriate approach for this prediction. Channel roughness and the presence of vegetation are the main flow resistance sources in most situations.

The influence of channel roughness on flow resistance depends on the ratio of flow depth, y to a representative sediment size, k. The D_{84} size (i.e. the size of the median axis of the bed material which is larger than 84 % of the material) is commonly used to represent k. According to their ratio, the roughness can be divided into large-scale, intermediate-scale and small-scale roughness (Bathurst et al 1981). The roughness is large-scale if the roughness elements affect the free surface, a condition when relative submergence, y/D_{84} (ratio of depth to sediment size) is less than 1.2. The roughness is intermediate-scale if the relative submergence, y/D_{84} lies between 1.2 and 4. When the relative submergence, y/D_{84} is higher then 4, the roughness is small-scale.

Vegetation plays a vital role in protecting the bed and banks from erosion, and preventing scour as well as providing environmental habitats for aquatic animals. On the other hand, vegetation increases flow resistance by increasing roughness and reducing channel capacity due to its bulk, increasing turbulence around trees, vines and brush; its effects therefore need to be fully understood in order to describe and predict river processes.

Flow resistance of small-scale, intermediate-scale and large-scale roughness as well as the influence of vegetation on flow resistance is discussed in the following sections.

4.2.1 Flow Resistance of Small–Scale Roughness

When we consider the flow resistance of small-scale roughness, the boundary resistance is the result of shear and pressure forces acting on the grains comprising the boundary, and the applied force per unit plan area is balanced by resisting forces

$$\tau_0 = \gamma RS \qquad 4.2$$

where τ_0 : shear stress at the boundary,

γ : specific weight of fluid,

R : hydraulic radius, and

S : longitudinal slope.

The proportionality between boundary shear and average flow velocity can be described by (e.g. Henderson, 1966)

$$\tau_0 = a\rho V^2 \qquad 4.3$$

where a : dimensionless coefficient,

ρ : fluid density, and

V :average flow velocity.

Combining equations (4.2) and (4.3) gives

$$V = \sqrt{\frac{g}{a} RS} \qquad 4.4$$

where g : gravitational acceleration.

Various equations, based on the assumed proportionality between boundary shear and average flow velocity have been proposed. All of these account for the resistance processes with a single coefficient of resistance (Bathurst, 1982). The most commonly used equations are the following:

Darcy-Weisbach:

$$V = \sqrt{\frac{8g}{f}} \sqrt{RS} \qquad 4.5$$

where *f* : Darcy-Weisbach friction factor.

Chézy:

$$V = C\sqrt{RS} \qquad 4.6$$

where *C* : Chézy resistance coefficient.

Manning:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \qquad 4.7$$

The Manning's equation has come to be the most widely used resistance equation in practical river hydraulics. Tables of values of Manning's *n* for different surface roughnesses are presented in most open channel flow textbooks.

Various refinements have been made to the friction factor estimation. The ASCE Task Force on Friction Factors in Open Channels (1963) reviewed the information available at the time and recommended using *f* rather than *n* because it correlates better with experimental data over a wide range of conditions. The following equations are recommended for estimating *f*.

For hydraulically rough flow:

$$\frac{1}{\sqrt{f}} = c\log\left(\frac{aR}{k_s}\right) \qquad 4.8$$

For hydraulically smooth flow:

$$\frac{1}{\sqrt{f}} = c\log\left(\mathrm{Re}\frac{\sqrt{f}}{b}\right) \qquad 4.9$$

For transitional flow:

$$\frac{1}{\sqrt{f}} = -c\log\left(\frac{k_s}{aR} + \frac{b}{\mathrm{Re}\sqrt{f}}\right) \qquad 4.10$$

The Task Force presented values of the coefficients *a*, *b* and *c* derived from various data sets. Representative values are

a=12
b=2.51
c=2

Values of k_s for concrete and masonry surfaces are presented in most open channel textbooks. Values range from 0.15 mm for very smooth concrete to 1.5 mm for gunite or shot concrete to greater than 5 mm for rubble masonry.

4.2.2 Flow Resistance of Intermediate-Scale Roughness

From laboratory experiments (Bayazit, 1976) it was found that once relative submergence, y/k exceeds value of 3.3, the resistance of the flow is higher than that predicted by the logarithmic resistance equation (4.8) for small-scale roughness, therefore the resistance equations for small-scale roughness are not appropriate for these cases. When the relative submergence, y/k lies between 1 and 3.3, both, form drag and skin friction contribute significantly to flow resistance, and the roughness is intermediate-scale.

The total shear stress, τ_0 for the condition of the intermediate-scale roughness can be expressed in dimensionless form as the sum of two components (Roberts and Wright, 1973)

$$\frac{\tau_s}{\tau_0} + \frac{\tau_r}{\tau_0} = 1.0 \qquad 4.11$$

where τ_s : shear stress on the background surface, and

τ_r : effective shear stress due to drag of the discrete roughness elements.

The effective shear stress due to drag of the discrete roughness elements, τ_r is obtained as follows

$$\tau_r = \frac{\lambda F_d}{A_b} \qquad 4.12$$

where λ : large roughness elements concentration,

F_d : drag force of the roughness elements, and

A_b : base area of the roughness elements.

The roughness concentration is proposed to be defined by

$$\lambda = n\frac{A_b}{A_t} \qquad 4.13$$

where n : number of roughness elements with base area A_b in a total boundary area A_t.

The drag of the roughness element can be related to an approach velocity by

$$F_d = C_d \int_{A_p} \frac{1}{2}\rho \overline{V}^2 dA_p \qquad 4.14$$

where C_d :drag coefficient,

$\overline{V}$: approach velocity, and

A_p : projected area of the roughness element.

The drag coefficient, C_d was determined to be 1.70 from an experimental study by Mirajgaoker and Charlu, (1963) who studied flow in flume with sand and gravel.

Hey (1979) fully modified the Colebrook-White equation (4.8) making explicit allowance for the effect of cross-sectional shape, difference in bed and bank roughness and nonuniform sediment on the resistance to flow

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{aR^{/}}{3.5D_{84}}\right) \qquad 4.15$$

where a :coefficient varies with the cross-sectional geometry of flow, and

$R^{/}$: effective hydraulic radius.

Field data were used to evaluate the proposed flow resistance equation (4.15). The equation (4.15) is recommended to use when R/D_{84} is higher then 1 (Thorne and Zevenbergen, 1985).

The friction factor equation for fully developed turbulent flow has also been expressed in power form, i.e.

$$\frac{1}{\sqrt{f}} = a\left(\frac{y}{D_g}\right)^{b} \qquad 4.16$$

where a : coefficient,

b : exponent, and

D_g : sediment characteristic.

Field data from 67 natural gravel-bed rivers in Alberta, Canada were used for development of the friction factor equations for different sediment characteristics by Bray (1979), i.e.

$$\frac{1}{\sqrt{f}} = 1.78\left(\frac{y}{D_{90}}\right)^{0.268} \qquad 4.17$$

A friction factor equation for the variation of $1/f^{1/2}$ with R/D_{50}, based on 136 field data sets obtained from New Zealand gravel bed rivers for the relative submergence of $1<R/D_{50}<200$ was proposed by Griffiths (1981), i.e.

$$\frac{1}{\sqrt{f}} = 1.33\left(\frac{R}{D_{50}}\right)^{0.287} \qquad 4.18$$

The equation covers two roughness categories, intermediate and small-scales roughness.

4.2.3 Flow Resistance of Large-Scale Rroughness

Although the complex phenomenon of flow resistance of large-scale roughness has a long research history, there is still today no reliable equation applicable for different cases where the flow depth and roughness elements height are of the same order of magnitude. Studies of flow resistance of large-scale roughness started with regard to mountain rivers (Hartung and Scheuerlein, 1967; Scheuerlein, 1973; Ashida and Bayazit, 1973; Bathurst, 1978; Bathurst and Simons, 1981; Griffiths, 1981, Jarrett, 1984, Thorne and Zevenbergen, 1985; Jonker et al, 2001). Physical features of mountain rivers that distinguish them from other rivers are steep slopes, wide bed material size distributions ranging from sand to boulders, and flow depths similar to bed material size.

The flow resistance of large-scale roughness is caused by the form drag of the boulders, free surface distortion and hydraulic jumps (Thorne and Zevenbergen, 1985). In real flow, roughness elements have a non-uniform distribution of size and this results in a non-uniform vertical velocity distribution different from the familiar semi-logarithmic one. The resistance of large-scale roughness depends on channel shape (the ratio of width to depth), roughness spacing (the ratio of the frontal cross-sectional area of an element to the area of boundary per element) and relative roughness. Judd and Peterson (1969) quantified this dependence as

$$\left(\frac{8}{f}\right)^{1/2} = \frac{V}{(gRS)^{1/2}} = fn(\lambda_1)\left(\frac{y}{w}\right)^{7(\lambda_1 - 0.08)}\left(\frac{y}{D_{50}}\right)^{1/3} \qquad 4.19$$

where w : surface width of the flow, and

λ_1 : roughness spacing.

With large-scale roughness, the velocity profile is completely disrupted since the roughness elements act individually, producing a total resistance based mainly on the sum of their profile drag. Roughness geometry is therefore the most important resistive factor, while channel geometry is important only indirectly.

The drag force, F_d, of an object in flow of velocity $\overline{V}$, is

$$F_d = \frac{1}{2}\rho A_p \overline{V}^2 C_d \qquad 4.20$$

where A_p : frontal cross-sectional area of the object, and

C_d : drag coefficient.

With assumption that drag force of isolated elements transferred to the bad as an effective bed shear, τ acting on area of bed A_b, the effective resistive stress is

$$\tau = \frac{\sum_1^n F_d}{A_b} = \frac{1}{2}\rho C_d \overline{V}^2 \frac{\sum_1^n A_p}{A_b} \qquad 4.21$$

where A_p : represented wetted frontal cross-sectional area (Bathurst, 1978).

Roughness spacing, λ_1 is the ratio of the frontal cross-sectional area of elements to the area of boundary per element:

$$\lambda_1 = \frac{\sum_1^n A_p}{A_b} \qquad 4.22$$

If resistive stress is (Henderson, 1966):

$$\tau_0 = \rho g y S \qquad 4.23$$

then combination of equations (4.22), (4.23) and (4.25) gives the resistance coefficient, *f*, as (Bathurst, 1978):

$$\left(\frac{8}{f}\right)^{1/2} = \frac{V}{(gyS)^{1/2}} = \left[\frac{1}{\frac{1}{2}C_d\lambda_1\left(\frac{\overline{V}}{V}\right)^2}\right]^{1/2} \qquad 4.24$$

where V : mean velocity (the ration of the discharge to the flow area), and

$\overline{V}$: approach velocity (the velocity upstream at each element).

Smart et al (2002) applied the same assumption, and the drag force F_d of an isolated bed element acting on area of bed A_b was expressed as

$$F_d = \frac{1}{2} C_d \rho \overline{V}^2 A_p = \tau_s A_b = \tau_s s_2 d_y d_x \qquad 4.25$$

where d_x : size dimension on flow direction,

A_p : protruding cross-sectional area perpendicular to the approach velocity, $\overline{V}$:

$$A_p = s_1 d_y d_z \qquad 4.26$$

where s_1 and s_2 : shape related factors,

d_y and d_z : width and height of roughness element respectively.

For a semielliptical element $s_1 = s_2 = \pi/4$, and the average shear stress over a particular area of the bed is

$$\tau_0 = \tau_s p \qquad 4.27$$

where p : ratio of A_b to considered area.

Combining equations (4.25), (4.26) and (4.27) gives:

$$\overline{V}^2 = (2/C_d)(\tau_0 / p)(s_2 / s_1)(d_x / d_z) / p \qquad 4.28$$

In real flow sediment is not uniform in size and has a non-uniform size distribution. As a result, some boulders can protrude through water surface while others do not. Consequently, instead of all the boulders steadily increasing their drag as depth increases, the influence of the smaller and lower boulders decreases, while the influence of the larger and higher boulders increases. The resistance to flow therefore is related to the size, shape, spacing and size distribution of the roughness elements and the channel geometry. The size of the roughness elements is usually represented by the median axis of D_{84} of the particles. For sediment with non-uniform size distribution, the ratio of approach velocity to mean flow velocity, and therefore the drag, varies from boulder to boulder. Roughness spacing varies with the depth of the flow. When the relative roughness decreases towards unity and frontal concentration increases, the resistance coefficient should increases as well. Channel geometry parameters are accounted the variation of drag across the channel, caused by the variation of the ratio of approach velocity to mean flow velocity. Judd and Peterson, (1969) described this effect with the term

$$\left(\frac{y}{w}\right)^{7(\lambda_1-0.08)} \tag{4.29}$$

Based on field data, Bathurst (1978) proposed a resistance equation for relative submergence, R/D_{84} less then 1.5:

$$\left(\frac{8}{f}\right)^{1/2} = \frac{V}{(gRS)^{1/2}} = \left(\frac{R}{0.365D_{84}}\right)^{2.34}\left(\frac{w}{y}\right)^{7(\lambda_1-0.08)} \tag{4.30}$$

Thompson and Campbell (1978) proposed a new adjustment of the Darcy-Weisbach resistance equation for the large-scale condition. They fitted experimental and published field data, and proposed:

$$\left(\frac{8}{f}\right)^{1/2} = 5.656\left(1-\frac{0.1k_s}{y}\right)\log\left(\frac{12y}{k_s}\right) \tag{4.31}$$

where k_s : Nikuradse roughness expressed as $k_s = 4.5D_{50}$.

Both equations (4.30) and (4.31) were applied to predict mean velocity of two reaches of a typical mountain river, and it was recommended to use them for condition of y/D_{84} less than 1 (Thorne and Zevenbergen, 1985).

Further theoretical development on estimation of flow resistance of large-scale roughness was performed by Bathurst et al (1981). The proposed approach was tested using flume data, and as a result, a new basic resistance equation for large-scale roughness was developed. The equation is very complicated and required more field data for its application:

$$\left(\frac{8}{f}\right)^{1/2} = \frac{V}{(gyS)^{1/2}} = \left(\frac{0.28}{b}Fr\right)^{\log(0.755/b)} \times \left[13.434\left(\frac{w}{d_{y50}}\right)^{0.492} b^{1.025(w/d_{y50})^{0.118}}\right] \times \left(\frac{A_w}{wy'}\right) \quad 4.32$$

where b : effective roughness concentration,

Fr : Froude number,

w : channel width,

d_{y50} : roughness element cross-stream axis,

A_w : total wetted roughness cross-sectional area, and

y' : depth from a free surface to a bed datum level.

An attempt by Bathurst (1985) to calibrate equations such as Eq.4.15 to develop a flow resistance equation for large-scale roughness condition, resulted in the following equation:

$$\left(\frac{8}{f}\right)^{1/2} = 5.62\log\left(\frac{y}{D_{84}}\right) + 4 \quad 4.33$$

The equation (4.33) is based on field data of 16 sites of upland British rivers, for a range of the relative submergence, y/D_{84} of 0.4 to 11.5.

As a new attempt, Bathurst (2002) derived two power form equations for the variation of $(8/f)^{1/2}$ with relative submergence, y/D_{84} from published field data by Bathurst (1978), Bathurst (1985), Feistmantl (1996), Jarrett (1984), Judd and Peterson (1969), Maresova and Mares (1989), and Thorne and Zevenbergen (1985). The two equations apply to different range of channel slope, S:

$S<0.8\%$
$$\left(\frac{8}{f}\right)^{1/2} = 3.84\left(\frac{y}{D_{84}}\right)^{0.547} \quad 4.34$$

$S>0.8\%$
$$\left(\frac{8}{f}\right)^{1/2} = 3.10\left(\frac{y}{D_{84}}\right)^{0.93} \quad 4.35$$

All the above large-scale roughness relationships are for the Darcy-Weisbach equation, which is based on the assumption of resistance by surface shear. A different approach was followed by Jonker et al (2002), who assumed the weight component of flow to be balanced directly by drag force, without translating these to an effective bed shear. He thus proposed:

$$V = \sqrt{2g}\sqrt{\frac{DS_o}{C_x}} \qquad 4.36$$

where D : particle diameter, and

C_x : large scale roughness resistance coefficient.

Equation (4.36) was applied to available published data (Bathurst, 1978; Jarret, 1984, and Bathurst, 1985) and corresponding values of the resistance coefficient related to physical parameter of sediment size, D_{50} were calculated. Calculated values of resistance coefficient, C_x and relative submergence, R/D_{50} were plotted, and a power form equation of the resistance coefficient was derived:

$$C_X = 0.5285\left(\frac{R}{D_{50}}\right)^{-2.166} \qquad 4.37$$

4.2.4 Summary of Resistance Equations Developed for Intermediate-Scale and Large-Scale Roughness

From the above it can be seen that there a large number of resistance equations have been developed for intermediate-scale and large-scale roughness. Some of the resistance equations were developed and calibrated based on field data from gravel, cobble or boulder bed rivers, and these are listed in Table 4.1. The range of relative submergence used for the development of equations is given in the third column. It is obvious (Table 4.1) that data used for calibration covered more than one flow condition or scale (intermediate or large-scale). Only for the equation of Bathurst (1978) did the data used for the equation’s calibration correspond with just one (the large-scale roughness) flow condition. It has to be noted as well that the equation (4.36) was developed for large-scale regime while the resistance coefficient, C_x (equation (4.37) was developed based on data covering both the large and the intermediate scales. In this connection, application of these equations therefore requires understanding of the development limitations.

Table 4.1 Resistance equations

References	Equation	Relative submergence
Bathurst (1978)	$\sqrt{8/f} = (R/0.365D_{84})^{2.34}(W/d)^{7(\lambda_E - 0.08)}$	$0.37 \leq R/D_{84} \leq 1.32$
Bray (1979)	$1/\sqrt{f} = 1.36(d/D_{50})^{0.281}$	$5 \leq d/D_{50} \leq 166$
Hey (1979)	$1/\sqrt{f} = 2.03\log(aR/3.5D_{84})$	$0.7 \leq R/D_{84} \leq 17$
Griffiths (1981)	$1/\sqrt{f} = 0.76 + 1.98\log(R/D_{50})$	$1 \leq R/D_{50} \leq 200$
Griffiths (1981)	$1/\sqrt{f} = 1.33(R/D_{50})^{0.287}$	$1 \leq R/D_{50} \leq 200$
Jarrett (1984)	$n = 0.39S^{0.38}R^{-0.16}$	$0.6 \leq d/D_{84} \leq 11$
Bathurst (1985)	$\sqrt{8/f} = 5.62\log(d/D_{84}) + 4$	$0.4 \leq d/D_{84} \leq 11.4$
Jonker (2002)	$C_x = 0.5285(R/D_{50})^{-2.166}$	$0.6 \leq R/D_{50} \leq 10.7$

4.3 Drag Force

When the water depth is similar to the size of the bed material, individual roughness elements protrude through the water surface, and the flow resistance is caused by the form drag of the roughness elements and free surface distortion. Understanding of the influence of the drag force on overall flow resistance is therefore required. Most of the resistance equations proposed for the large-scale roughness condition are based on translation of element drag to equivalent bed shear, and evaluation of the drag force is therefore required for application of the equations.

A series of experimental studies related to the drag of hemispheres were conducted at Utah State University (Mason, 1965; Marajggaoker, 1961; Tullis, 1966). The results of the studies were used to identify the variables affecting the drag on a hemisphere for various flow conditions (Flammer et al, 1970). The important variables were identified as:

- Hemisphere Reynolds number, *Re*
- Froude number, *Fr*

- Velocity profile parameter, *P*
- Relative submergence, *y/k*, and
- Relative width, *w/2k*

where *y* : flow depth,
k : hemisphere radius, and
w : channel width.

The drag on a hemisphere was studied in six flow fields:

- Semi-infinite uniform,
- Semi-infinite nonuniform,
- Finite, uniform without a free surface,
- Finite, nonuniform without a free surface,
- Finite, uniform with a free surface, and
- Finite, nonuniform with a free surface

The semi-infinite flow field refers to conditions where both relative depth and relative width have no effect on the flow, while flow is considered to be finite where it is affected by the relative depth and the relative width.

The variation of the drag coefficient of a hemisphere with relative submergence and Froude numbers was plotted and shown in Figure 4.1.

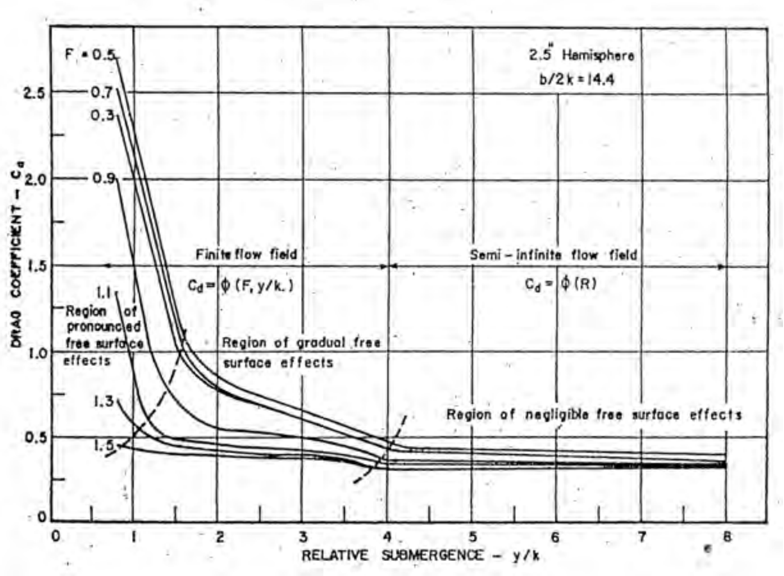

Figure 4.1 **Variation of C_d with relative submergence and Froude number showing three distinct regimes of flow for hemisphere (Flammer et al, 1970)**

Three regimes of flow were defined for the hemisphere, which are:

- A regime of pronounced free surface effects ($y/k \leq 1.6$),
- A regime of moderate free surface effects ($1.6 < y/k < 4.0$), and
- A regime of negligible free surface effects ($y/k > 4.0$)

The drag force on individual boulders on a riverbed was determined from field measurements under low flow regime condition, corresponding to the large-scale condition (Bathurst, 1996). Heights of the boulder and flow depth were equal. Drag was determined from the momentum deficit in the boulder wake, obtained by measuring the flow velocity in a traverse across the wake. The field measurements yielded a mean drag coefficient of 0.36.

The flow velocity was measured in a traverse across the wake of an object, far enough downstream that the difference between the static pressures in the wake and the free stream can be neglected. The drag coefficient C_d for the object is determined under the assumptions that there is a uniform field of approach velocity and that the object is very long in the flow direction normal to that in which the traverse is made

$$C_d = \frac{2}{w}\int_{wake} \frac{u}{V}\left(1 - \frac{u}{V}\right)dz \qquad 4.38$$

where C_d is defined by

$$C_d = \frac{F_d}{\frac{1}{2}\rho A V^2} \qquad 4.39$$

where u : velocity at distance z across the wake,
V : freestream velocity,
w : object width in z direction, and
A : cross sectional area of the object normal to the flow.

The drag coefficient value determined from the field measurement (0.36) is lower than laboratory derived values. This difference can be ascribed to the effect of the rough bed as well as element interaction. Generally, the field method of measuring boulder drag is potentially applicable in rivers, but only under carefully controlled conditions. Further tests are needed to define these conditions and examine the degree to which the assumptions behind the method can be accommodated in a natural flow environment.

4.4 Flow Resistance in Vegetated Channels

Vegetation is an important component of river ecosystems that creates habitat diversity for aquatic animals. On the other hand, the presence of vegetation in a channel influences overall flow resistance. For successful prediction of the flow resistance under low flow conditions, an understanding of the effect of vegetation on channel hydraulics is essential.

The retarding effect of vegetation on flow resistance has long been recognised, and approaches to predict flow resistance in vegetated channels, have been developed. These approaches are generally based on the conventional open channel equations, with effective resistance coefficients determined experimentally or through estimation of the drag coefficient for vegetation elements (Klaassen and van der Zwaard, 1974; Christensen, 1976; Thompson and Roberson, 1976; Kao and Barfield, 1978; Turner and Chanmeesri, 1984; Kadlec, 1990; Smith et al, 1990; Hall and Freeman, 1994; Kouwen and Moghadam, 1996; Nepf and Vivoni, 1998; Wu el at, 1999).

A method for estimating Manning's *n* for shrubs and woody vegetation accounting for the influences of horizontal plane density, stem diameter, and the height and width of the leaf mass of typical plant on flow resistance was developed by Freeman et al (1998). The equation for the estimation of Manning's *n* value under submerged flow conditions ($y > 0.8\,H$) is given by

$$n_{veg} = 0.039 k_n \left(\frac{E_s A_s}{\rho V^2 A} \right)^{0.141} \left(\frac{H}{y} \right)^{0.175} (MA)^{0.191} \left(\frac{\nu}{VR} \right)^{0.0155} \qquad 4.40$$

and Manning's *n* value for emergent condition ($y < 0.8\,H$) is

$$n_{veg} = 2.2x10^{-6} k_n \left(\frac{E_s A_s}{\rho V^2 A_*} \right)^{0.242} \left(MA_* \right)^{0.0623} \left(\frac{\nu}{VR} \right)^{0.662} \qquad 4.41$$

where A : frontal area of an individual plant blocking flow (ft^2),
A_* : net submerged frontal area of a partially submerged plant (ft^2),
A_s : total cross sectional area of the stem of an individual plant (ft^2),
E_s : modulus of plant stiffness (lb/ft^2),
H : average undeflected plant height (ft),
k_n : unit conversion for Manning's equation (1 for SI, and 1.49 for imperial units),
M : relative plant density (number of plants per ft^2) ,
W : width of average plant (ft), and
ν : fluid dynamic viscosity (ft^2/s).

A flow resistance prediction method for densely vegetated flood plains has been developed by Petryk and Bosmajian (1975):

$$n = n_b \sqrt{1 + \left(\frac{C_d \sum A_i}{2gAL} \right) \left(\frac{1.49}{n_b} \right)^2 R^{3/4}} \qquad 4.42$$

where n_b : Manning's boundary roughness coefficient, excluding the vegetation,

C_d : effective drag coefficient for the vegetation in the direction of flow,

$\sum A_i$: projected vegetation area in the streamwise direction,

L : channel length ,

A : cross-sectional area of flow, and

1.49 : correction factor for imperial units (or 1.0 for S.I. units).

The vegetation density, Veg_d, in the cross section is given by:

$$Veg_d = \frac{\sum A_i}{AL} \qquad 4.43$$

The drag force on each plant described by

$$D_i = \frac{C_d \gamma \overline{V}_i^2 A_i}{2g} \qquad 4.44$$

where $\overline{V_i}$: average approach velocity to the i^{th} plant.

In this model it is assumed that average approach velocity, $\overline{V_i}$ is equal to the mean velocity, V. The limitations of this model require that the velocity is small enough to prevent a large degree of plant bending, the vegetation is distributed relatively uniformly in the lateral direction, large variations in average velocity do not occur across the channel, the maximum flow depth is less than or equal to the maximum height of vegetation, and large variations in flow velocity do not occur over the flow depth.

The hydraulics of shallow, non-submerged flow in a densely vegetated channel cannot be treated using Manning's roughness relationship, mainly due to the fact that, with the water flowing among the randomly patterned vegetation blades, drag resistance, instead of shear resistance, becomes the dominant component in the analysis of the mechanics of the flow system.

An alternative form of equation for condition where dominant resistance arises from stem drag proposed by James et al (2001)

$$V = \frac{1}{F}\sqrt{S} \qquad 4.45$$

with F

$$F = \frac{1}{\sqrt{\frac{2g}{C_d N d}\left(1 - \frac{N\pi d^2}{4}\right)}} \qquad 4.46$$

in which N :number of stems per square meter, and

d :stem diameter

For shallow flows the bed roughness influence can be accounted by replacing F by F_b

$$F_b = \frac{1}{\sqrt{\left(\frac{1 - \frac{N\pi d^2}{4}}{\frac{f}{8} + \frac{1}{2}C_d N y d}\right) g y}} \qquad 4.47$$

Li and Shen (1973) developed a mathematical model, as an extension of the approach of Petryk (1969) and Yano (1966), to describe the mean flow properties in an open channel with a multicylinder distribution. The model predicts the drag on each cylinder for given conditions. The following input data are required:

- size and distribution of cylinders,
- discharge,
- slope and width of channel,
- local coefficient of drag of cylinders, and
- flow depth.

The model has the following assumptions:

- the flows are steady and uniform;
- linear superposition of the velocity defect is valid;

- the boundary shear stress is uniformly distributed over the bed;
- the form resistance is assumed to be entirely due to vegetation; and
- the bed form resistance is negligible.

A resistance model for flow through emerged reeds (REEDFLO v2) was developed by James et al (2001) for uniform flow conditions within homogeneous arrangements of rigid, vertical stems. The model is based on a force balance approach (Li and Shen, 1973; Petryk and Bosmajian, 1975; Christensen, 1976; Lindner, 1982; and Kosorin, 1983), where the applied force is balanced against the bed resisting forces and vegetation drag components.

The resistance model (REEDFLO v2) was utilized to develop a general resistance equation for practical application. Sensitivity analysis of the flow resistance model (REEDFLO v2) showed roughness coefficient, k_s to be insignificant for vegetated streams where stem drag resistance dominates. Various conditions were simulated for a wide range of input parameters. The parameters were varied systematically to explore their effects on flow resistance. The proposed equation is (James et al, 2001):

$$F = 1.89\left(\frac{a}{D}\right)^{-0.65}\left(\frac{D}{y}\right)^{0.07} C_D^{0.48} \qquad 4.48$$

where F : resistance coefficients,

a : stem spacing,

D : stem diameter,

Y : flow depth, and

C_D : stem drag coefficient.

4.5 Velocity and Depth Distributions with Large-Scale Roughness

Flow velocity and depth distributions represent the hydraulic habitat variability in a natural stream. Environmental flow requirements assessments as well as Reserve determination studies require estimation of hydraulic habitat availability related to different discharges. Prediction of velocity and depth distributions therefore becomes essential. Statistical descriptions of the velocity and depth distributions as a function of hydraulic parameters such as discharge, mean roughness, mean width, and mean depth, is a potentially useful approach for providing the necessary information.

The probability distribution of velocities in regular and highly irregular natural stream cross sections follows a power law (Dingman, 1989):

$$F(v) = (v / V)^c \qquad 4.49$$

where *v* : local flow velocity,
V : maximum cross-sectional velocity, and
c : shape parameter equal to 1/*b*, and
b : slope of a plot of *v* versus V*(v)*on log-log scale.

Detailed field velocity measurements as well as stream slopes, channel roughness characteristics, and stream sizes from nine cross-sections of river streams were used for Dingman's study. Values of the shape parameter, *c* were calculated from the field data, and they range from 0.356 to 0.942 for an extensive sample, and from 0.164 to 0.6118 and from 0.497 to 0.912 for intensive samples for pool and riffle cross sections respectively. There is no clear procedure for estimation of the maximum cross-sectional velocity, *V* and the shape parameter, *c*. Further investigation therefore is required for development of the approach to the stage of a practical application.

Lamouroux et al (1995) analyzed velocity data of 37 French stream reaches, and developed a statistical model for predicting velocity frequency distributions. A shape parameter of velocity distribution, *s* was suggested as:

$$s = -0.275 - 0.237\ln(Fr) + 0.27(D / H) \qquad 4.50$$

where *D* : averaged dominant roughness, and
H : averaged reach depth,

The density of probability of *u/U* is given by:

$$f(x,s) = s\left\{3.33\exp\left(-\frac{x}{0.193}\right) + 0.117\exp\left[-\left(\frac{x-2.44}{1.73}\right)^2\right]\right\} + (1-s)\left\{0.653\exp\left[-\left(\frac{x-1}{0.864}\right)^2\right]\right\} \qquad 4.51$$

where s : shape parameter of the point velocity distribution,

u : point velocity,

U : averaged reach velocity, and

x : relative point velocity, equal to u/U.

A similar approach was applied by Jonker et al (2001) to predict the velocity distribution of local flow velocities in cobble and boulder rivers of the Western Cape during low flows. The rivers are characterized by different types of morphological units, and three dominant morphological units were recognized. These units are pool, plane bed, rapid and riffle. Through analyses of the velocity data it was found that within pool, rapid and riffle morphological units the distribution of local sets of point velocities could be related to the average velocity, flow depth, flow width and relative roughness within a cross-section, and used to predict the frequency distribution of point velocity in these morphological units. For plane bed morphological units, no statistically significant relationships were found. Based on these results it was concluded that:

- The Weibull distribution provides the best estimate of the frequency distribution of the relative point velocities within pool morphological units.
- The Weibull and Extreme distributions both provide the best fit to the observed data within the plane bed morphological units.
- Within rapid and riffle morphological units the Extreme distribution displays the best fit to the observed data, followed by the Weibull distribution.

Besides the velocity, the flow depth is a hydraulic parameter that is used by biologists to describe hydraulics habitat in stream reaches (Chapter 3). Lamouroux (1998) proposed depth probability models developed based on analyses of data from a wide range of streams. It has been found that depth probability distributions tend from exponential to normal with increasing stage. The depth probability distribution was expressed as:

$$f(x,t) = t\exp(-x) + (1-t)\,0.951\exp\left[-\left(\frac{x-1}{0.593}\right)^2\right] \qquad 4.52$$

where t : mixing parameter varying from 0 (normal distribution) to 1 (exponential distribution),

x : relative depth, equal to h/H (h is flow depth, and H is mean reach depth).

4.6 Conclusions

From the above literature survey, it can be seen that many investigations have been carried out to predict the flow resistance of large-scale and intermediate-scale roughness. A number of equations (semi-logarithmic and power) have been developed (Table 1). Furthermore, it is clear that the flow field over a rough surface with small submergence differs remarkably from that with large relative submergence (Bayazit, 1975; Bathurst, 1978; Bathurst, 1981; Bathurst, 1985; Thorne and Zevenbergen, 1985; Bray and Davar, 1987; Dittrich and Koll, 1997; Lawerence, 1997.) Therefore, equations for prediction of flow resistance for different conditions must account differently for resistance components related to different flow regimes.

Some of the equations were developed based on experimental or field data. Other equations were proposed as modifications of the well-known Manning's, Chezy or Darcy-Weisbach equations. Application of all these equations requires an understanding of limitations of their development.

Chapter 5

HYDRAULIC CHARACTERISTICS ASSOCIATED WITH LARGE-SCALE ROUGHNESS

LABORATORY EXPERIMENTS

5.1 Introduction

From the literature review (Chapter 4) it was found that in most cases, the development of resistance equations was based on laboratory or field data, representing more than one roughness scale. Other investigations have described three types of flow regime related to three (small, intermediate and large) scales (Lawrence, 1997; Lawrence, 2000; Nikora et al, 2001; Smart et al, 2002), and different modifications of Darcy-Weisbach friction factor *f* for application on appropriate condition have been proposed.

The modification of resistance coefficients such as Manning's *n*, the Chézy *C* and the Darcy-Weisbach *f*, that were developed for small-scale roughness resistance, is not the only approach for predicting the flow resistance under large-scale and intermediate-scale roughness conditions. Flow resistance of large-scale roughness is related mainly to the form drag of the elements and their disposition in the channel (Bathurst, 1981). Furthermore individual roughness elements within a natural channel vary in number, size, shape and distribution. It can be seen that there are a large number of variables that affect flow resistance. Laboratory experiments have been performed to gain better understanding of flow resistance under large-scale roughness conditions.

An experimental programme was carried out to investigate the flow resistance of large-scale roughness. The experiments were performed in laboratory flume under controlled and idealized situations in order to understand the influence of the different resistance factors. The aim of the study was to establish the effects of large-scale elements on flow resistance under different hydraulic conditions determined by bed slope and discharge as well as to develop resistance prediction methods. Experiments were carried out using different shapes of roughness element and different densities.

The influence of bed roughness on overall flow resistance changes with relative submergence, ratio of a flow depth, *y*, to a roughness height, *h*. Experiments were therefore performed under both emergent and submerged conditions.

5.2 Laboratory Investigation on Flow Resistance of Large-Scale Roughness

The experimental work on an investigation of influence the large-scale roughness on flow resistance was carried out at the hydraulic laboratory of the School of Civil and Environmental Engineering. Two shapes of roughness element, cylindrical and hemispherical, were tested.

To simplify interpretation of the experimental results, cylinders as roughness elements with outside diameter of 66 mm were used in the Series A experiments. Tests of Series A were all performed with a smooth bed. The first set of experiments was carried out without the roughness elements to estimate the basic resistance of the smooth bed.

Series B experiments were performed using cylinders with D=50 mm placed on both, smooth and rough beds. The rough bed was created by rubber matting with a "stringy mesh " type of surface called Nomad matting. The effective roughness of the rough bed was determined by running the experiments without the roughness elements. A summary of the experiments of Series A and B is presented listed in Table 5.1.

Roughness elements simulated by hemispherical shells of constant shape and size were used in Series C experiments. The shells were constructed of concrete with a diameter of 114mm. The experiments of Series C were performed for the hydraulic conditions listed in Table 5.1.

All experiments were carried out with roughness elements arranged in staggered grid pattern with equal longitudinal (*a*) and transverse (*b*) spacing (Fig. 5.1). Information of spacing used at each experiment is presented in Table 5.1.

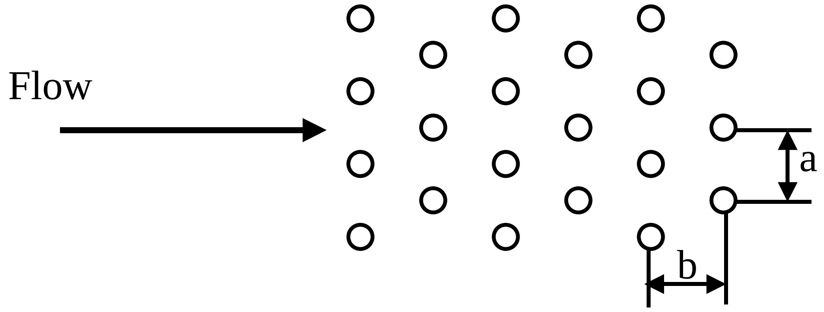

Figure 5.1 **Roughness elements arrangement used in experiments**

Table 5.1 **Experimental conditions of Series A, B and C**

Test	Shape	*D* (mm)	Density (N/m^2)	*a, b* (mm)	Bed	Slope	Discharge (l/s)
Tests A1-A2					Smooth	0.00057-0.0057	1.60-27.30
Tests A3-A5	Cylinder	66	40	157	Smooth	0.00057-0.0057	0.14-2.14
Tests A6-A8	Cylinder	66	12	314	Smooth	0.00057-0.0057	0.17-5.64
Tests B1-B2					Rough	0.0022-0.0045	6.00-28.00
Tests B3	Cylinder	50	47	150	Rough	0.0045	0.42-18.90
Tests B4-B5	Cylinder	50	47	150	Smooth	0.00163-0.0073	0.25-9.65
Tests B6	Cylinder	50	92	100	Rough	0.0045	0.88-18.4
Tests B7-B9	Cylinder	50	92	100	Smooth	0.00163-0.0073	0.25-10.50
Tests B10-B11	Cylinder	50	159	75	Rough	0.0022-0.0045	0.26-14.25
Tests B12-B14	Cylinder	50	159	75	Smooth	0.00163-0.0073	0.20-11.40
Tests C1-C4	Hemisphere	114	56	133	Smooth	0.0012-0.0064	0.11-63.00

5.2.1 Experimental Procedure

The experiments were all conducted in a 0.38 m wide, 15.0 m long, glass-sided tilting laboratory flume under controlled and idealized conditions. A tailgate fixed downstream of the flume was used to control the flow depth in the channel to ensure uniform flow.

Water was supplied to the flume through a closed circulation system, and two valves situated in the supply pipe at the head of the experimental flume were used to control the discharge. The discharge was varied by opening/closing these control valves and measured using V-notch, which was installed at the downstream end of the flume, and an electronic flow meter with sensors that are situated in the water pipe that discharges into the flume.

All experiments were carried out under uniform conditions. To estimate the uniform flow depth for a given discharge the following procedure was applied:

- For a particular discharge, the height of the downstream tailgate was adjusted several times to obtain different flow depths and surface slopes. Measurements of the height of the tailgate position were taken.

- Stilling pot or a pointer gauge measurements were used to calculate a corresponding surface slope and an average depth for each height of the tailgate.

- Calculated surface slopes as well as the flume slope, and the average depths were plotted against the tailgate heights. At the point where the trend line of surface slope crossed the flume slope line, the tailgate height was evaluated. This tailgate height was then used to determine the average depth for uniform flow using the trend line fitted to the plot of the average depth vs. tailgate height.

The procedure, mentioned above, was used to estimate the depth related to the uniform flow. Several heights of the down-stream tailgate were tested for each discharge to insure that a uniform surface slope was obtained.

Experimental conditions and results of Series A, B and C experiments are described in the sections below.

5.2.2 Series A Experiments

Series A experiments were performed with artificial cylinders of D=66 mm as roughness elements. Experiments were carried out under emergent conditions where the roughness elements penetrated the water surface.

5.2.2.1 Basic Resistance

The first set of experiments was conducted in the smooth bed without cylinders in order to establish the friction resistance characteristics of the bed surface. The experiments were performed for five different discharges at slope of 0.00571. Measured stage-discharge data was used to calculate the average velocity and the hydraulic radius for a given discharge. The friction factor, *f*, and the Reynolds number were then calculated, and are presented in Appendix , Table 1 (tests A1-A2).

A side-wall correction procedure of the Vanoni and Brooks (1957) was applied to determine the friction factor of the bed. The results of the analysis are presented in Table 5.2, below.

Table 5.2 Hydraulic parameters and friction factors of smooth bed

Q (l/s)	4.66	10.17	18.67	23.19	27.30
y (m)	0.020	0.035	0.055	0.066	0.070
S	0.0057	0.0057	0.0057	0.0057	0.0057
R_f (m)	0.0181	0.0296	0.0427	0.0490	0.0512
R_b (m)	0.0181	0.0304	0.0457	0.0543	0.0555
f_b (m)	0.0216	0.0233	0.0257	0.0285	0.0236
Re_b	38918	81530	143286	176276	199690
n	0.0085	0.0096	0.0108	0.0117	0.0107

where: Q : discharge,

y : flow depth,

S : slope,

R_f : hydraulic radius (flume),

f_b : friction factor (bed),

f_b : friction factor (bed),

Re_b : reynolds number (bed), and

N : Manning's (bed).

5.2.2.2 Effects of Roughness Element Density and Slope on Overall Resistance

The stage-discharge relationships for the basic channel (S=0.00057 and S=0.00570) and two different densities at slopes of 0.00057, 0.00114 and 0.0057 are presented in Fig. 5.2. Dotted and solid single lines represent stage-discharge relationships for the basic (smooth) channel. Graphs related to densities 1 and 2 are marked in the legend as 1 and 2, respectively.

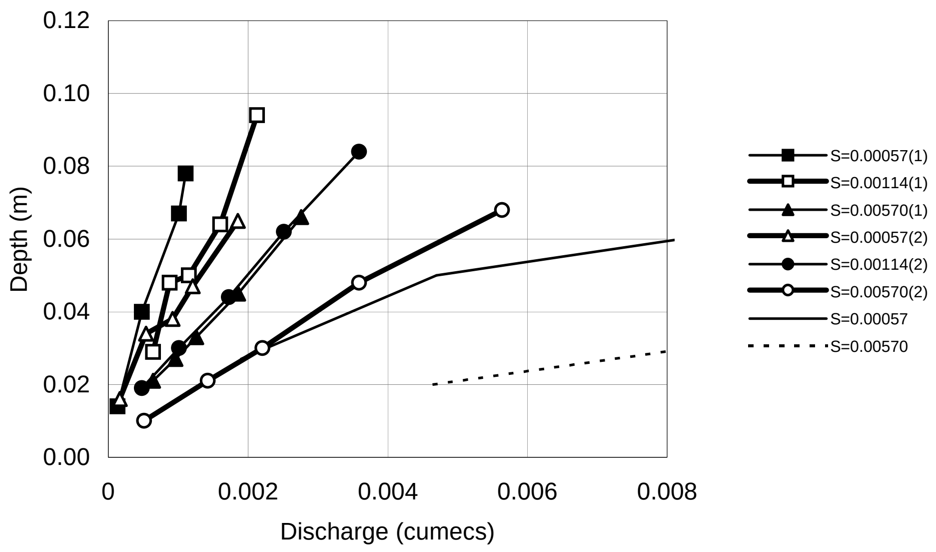

Figure 5.2 **Stage-discharge relationships for different densities and slopes, Series A1 experiments**

As expected, the cylinder density has a significant effect on overall flow resistance, and the flow depth for a given discharge is increased with increasing density.

The resistance characteristics of the different cylinder densities expressed in terms of Manning's *n* against the flow depth are shown in Fig. 5.3. Basic channel resistance in terms of Manning's *n* is also shown.

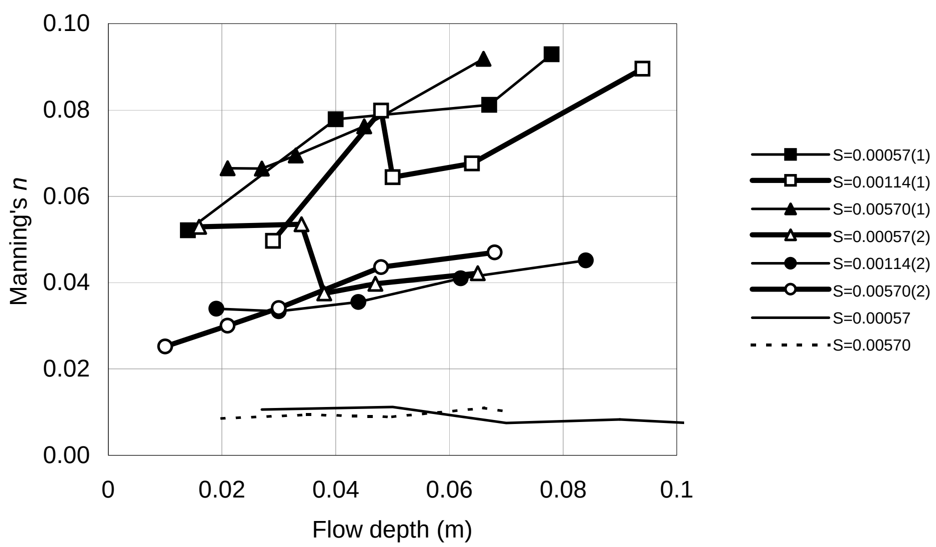

Figure 5.3 **Effect of cylinder density in terms of Manning's *n* Series A1 experiments**

From Fig. 5.3 it is clear that flow resistance in terms of Manning's *n* is higher for density 1 (40 No./m^2) then for density 2 (12 No./m^2). Furthermore it can be seen that Manning's *n* varies significantly with flow depth for densities 1 and 2, while for the basic channel it remains about constant.

The Series A experiments were performed at three different slopes (0.00571, 0.00114 and 0.00057) for each density. The results in terms of Manning's *n* variation with flow depth for each cylinder density and channel slope show that influence of channel slope is not significant and is inconsistent (Fig. 5.3).

5.2.3 Series B Experiments

The Series B experiments were conducted with cylinders with *D*=50 mm. Experiments were carried out for both emergent and submerged conditions. The experiments were performed for smooth (tests B4-5, B7-9, and B12-14) and rough (tests B3, B6 and B 10-11) beds. Basic resistance of the rough bed was tested as well (tests B1 and B2). Experimental conditions of Series B are listed in Table 5.1.

5.2.3.1 Basic Resistance of Rough Bed

An artificial rough bed was placed on the flume bottom and its resistance characteristics were determined through experiments without the roughness elements. The experiments were conducted at two slopes (0.0022 and 0.0045). Four discharges at each slope were used and the corresponding flow depths were measured and listed in Table 2, Appendix (tests B1.1 to B1.4, and B2.1 to B2.4).

The side-wall correction procedure of the Vanoni and Brooks (1957) was applied in order to estimate the friction of the bed and the wall, and hydraulic parameters and calculated friction factors are presented in Table 5.2. Friction factors of the smooth and the rough bed, f_b and the wall, f_w are plotted against flow depths in Fig. 5.4. In the figure (Fig.5.4) graphs related to the rough and smooth beds labelled as "RB" and "SB" respectively.

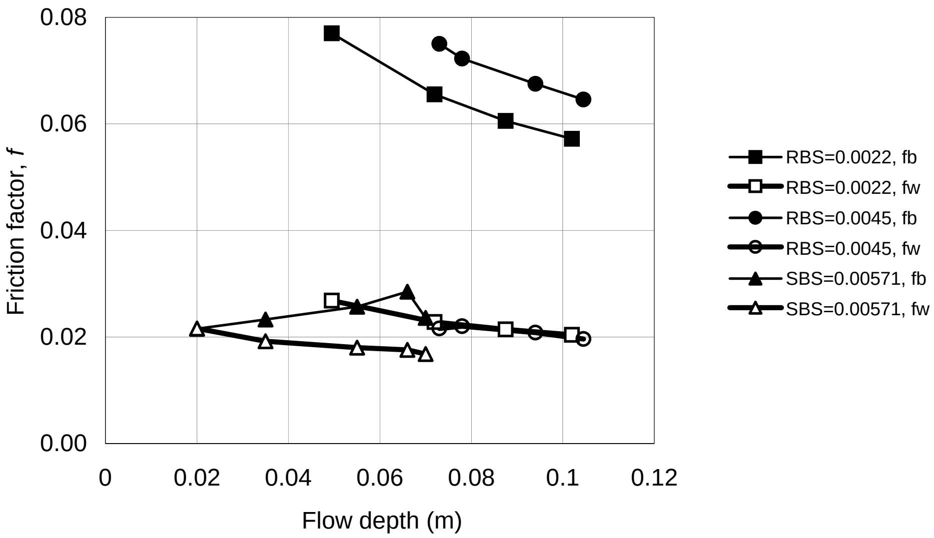

Figure 5.4 Friction factors of rough and smooth beds and wall

The effective roughness of the rough bed (k_s) was calculated by rearranging the Colebrook-White transition formula

$$k_s = 12R\left(10^{\frac{1}{-2\sqrt{f}}} - \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \qquad 5.1$$

where R :hydraulic radius (bed),

Re :Reynolds number, and

f :friction factor.

Calculated values of k_s are included in Table 5.2.

Table 5.2 Hydraulic parameters and friction factors of rough bed

Q (l/s)	6.0	11.2	15.4	19.7	15.5	17.4	23.5	28.0
y (m)	0.0495	0.0720	0.0875	0.1020	0.0730	0.0780	0.0940	0.1045
S	0.0022	0.0022	0.0022	0.0022	0.0045	0.0045	0.0045	0.0045
R_f (m)	0.039	0.052	0.060	0.066	0.053	0.055	0.063	0.067
R_b (m)	0.045	0.064	0.075	0.086	0.066	0.069	0.082	0.090
f_b (m)	0.077	0.066	0.061	0.057	0.075	0.072	0.067	0.065
k_s (m)	0.0085	0.0084	0.0083	0.0083	0.0117	0.0114	0.0116	0.0115

5.2.3.2 Influence of Roughness Element Density on Flow Resistance

The influence of roughness element density on overall flow resistance was tested at slopes of 0.00163, 0.0045 and 0.0073 for the smooth bed and at slopes of 0.0022 and 0.0045 for the rough bed. Stage-discharge relationships are plotted in Figs. 5.5 and 5.6 for smooth and rough beds experiments respectively. The curves identified as 1, 2 and 3 represent stage-discharge relationships of density 1, density 2 and density 3 respectively.

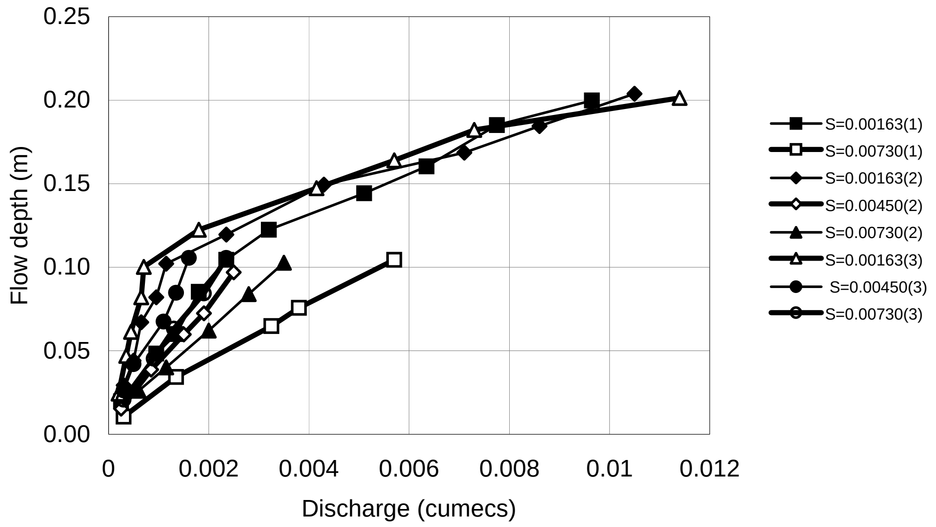

Figure 5.5 Stage-discharge relationships for the smooth bed

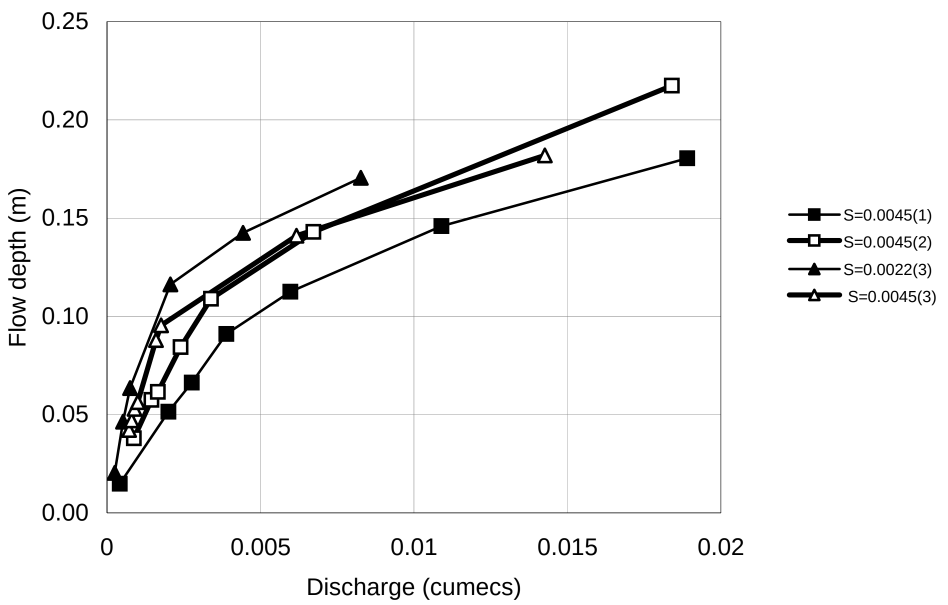

Figure 5.6 Stage-discharge relationships for the rough bed

The effect of roughness element density on flow resistance in terms of Manning's *n* with the relative submergence for smooth and rough beds is presented in Figs 5.7 and 5.8. Results indicate that resistance increases with roughness element densities, but it is clear as well that Manning's *n* varies significantly with flow condition. Furthermore, the Manning's *n* increases with relative submergence, and (as was expected) the highest Manning's *n* values occur for a relative submergence equal to one, whereafter values of Manning's *n* decrease with increasing relative submergence. At a relative submergence of 2, the three curves for density 1, density 2 and density 3 at slope of 0.00163 converge showing that above this level the density has no significant effect on flow resistance (Fig. 5.7).

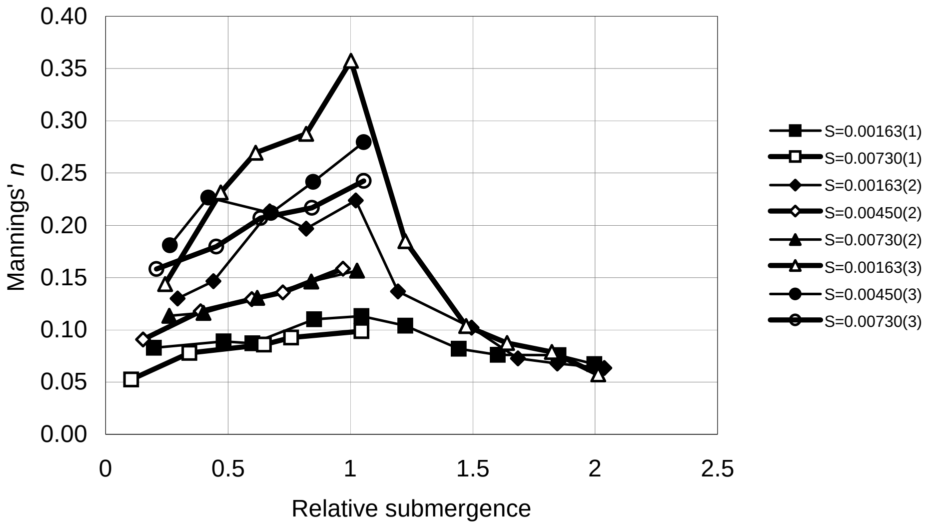

Figure 5.7 Manning's *n* variation with relative submergence for Densities 1, 2 and 3, for smooth bed experiments

Average velocities from measured stage-discharge data were calculated as the ratio of the discharge and the flow area for experiments, which were performed for a wide range of relative submergence (tests B4, B7 and B12 for the smooth bed, and B3, B6, B10 and B 11 for the rough bed). The average velocity values versus the relative submergence forsmoothand rough beds are plotted in Figs. 5.9 and 5.10 respectively.

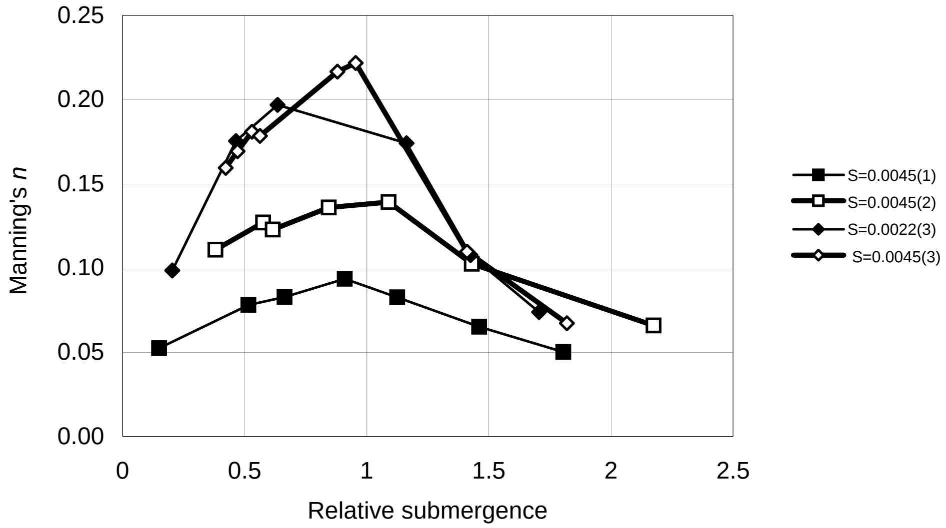

Figure 5.8 Manning's *n* variation with relative submergence for Densities 1, 2 and 3, for rough bed experiments

It can be seen that average velocity values are nearly constant for emergent conditions where the flow depths are less than or equal to the height of the roughness elements, for the relative submergence less or equal to 1, where the resistance is due mainly to the influence of roughness element drag. When the roughness elements are submerged (flow depth is higher then the height of the roughness elements) the average velocity varies significantly with flow condition (Figs. 5.9 and 5.10) because the roughness elements constitute a boundary roughness to the flow above.

5.2.3.3 Influence of Channel Slope on Flow Resistance

The Series B experiments were performed at three different slopes (0.00163, 0.0045 and 0.0073) and for two (smooth and rough) beds. The influence of channel slope on flow resistance in terms of Manning's *n* with relative submergence for the smooth and rough beds are presented in Figs. 5.7 and 5.8 respectively.

The results show that channel slope has some influence on resistance (Figs. 5.10 and 5.11). The influence of channel slope on resistance may not be direct; it can be a response to a change in roughness elements drag coefficient, Reynolds number, or hydraulic condition.

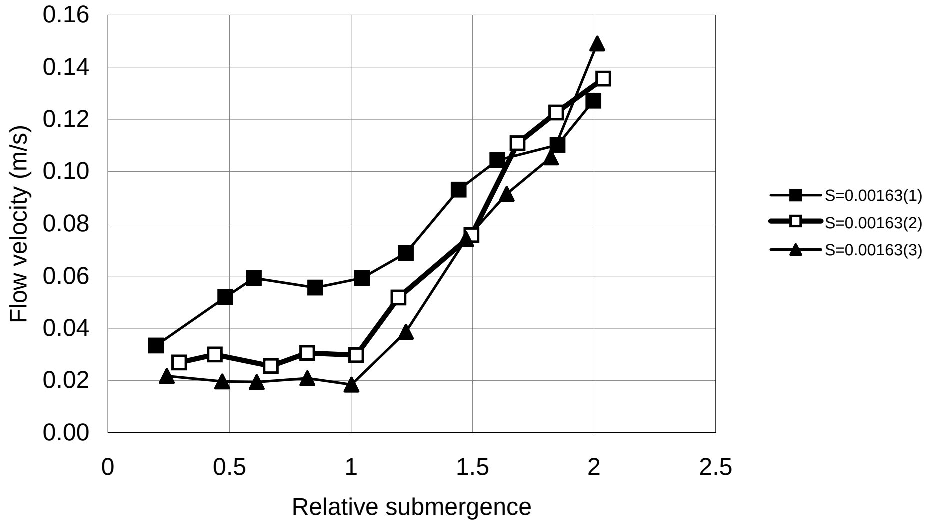

Figure 5.9 Average velocity calculated from stage-discharge data for smooth bed

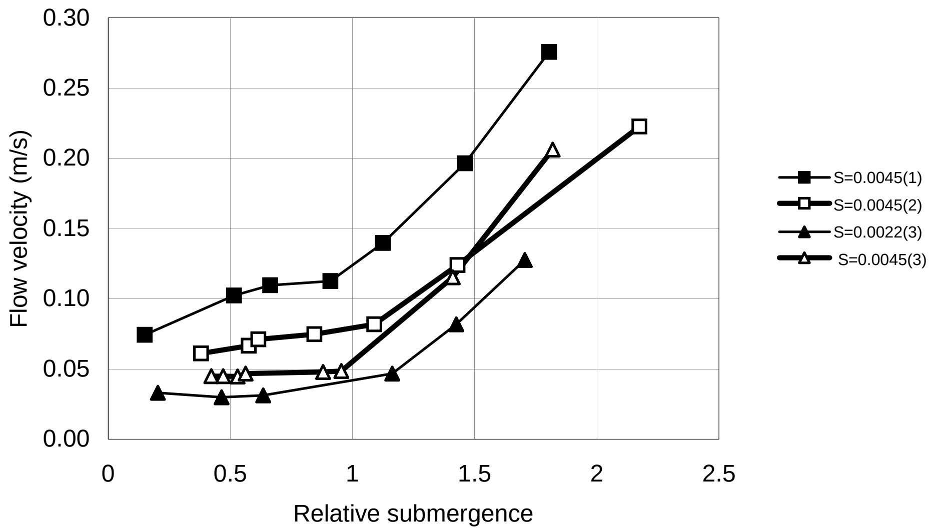

Figure 5.10 Average velocity calculated from stage-discharge measurements for rough bed

5.2.4 Series C Experiments

Series C experiments were conducted in the same flume as the experiments of Series A and B. Hemispheres of constant size were used as roughness elements. The hemispheres were moulded of concrete, with a diameter of 114mm and arranged in staggered grid pattern (Fig.5.1) with equal longitudinal and transverse spacing (133 mm center to center). The experiments were performed for one density of hemispheres only and four flume slopes.

Experimental conditions of Series C are listed in Table 5.1. All measurements of tests C1-C4 are included in Appendix, Table 5.

Stage-discharge relationships at slopes of 0.0012, 0.0024, 0.0049 and 0.0064 are showed on Fig. 5.11. Flow resistance in term of Manning's *n* variations versus the relative submergence is plotted in Fig. 5.12.

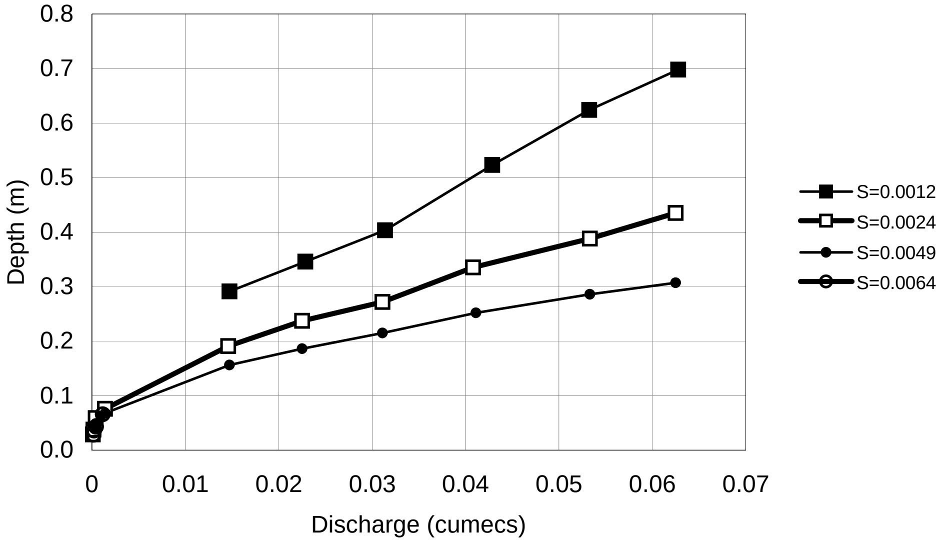

Figure 5.11 Stage-discharge relationship for Series C experiments

Flow resistance expressed by Manning's *n* varies with relative submergence (Fig. 5.12). It can be seen that flow resistance decreases with increasing relative submergence, and curves trend into three different subjections that can be related to submergence conditions. Flow resistance changes significantly for relative submergence less than 1, resulting from the relatively large contribution of the form drag of the roughness elements. When the relative submergence is bigger than 4, Manning's *n* remains about constant, with flow resistance accounted for as bed friction. The range of relative submergence from 1 to 4 lies in transitional regime, and both, form drag and skin friction contribute to flow resistance.

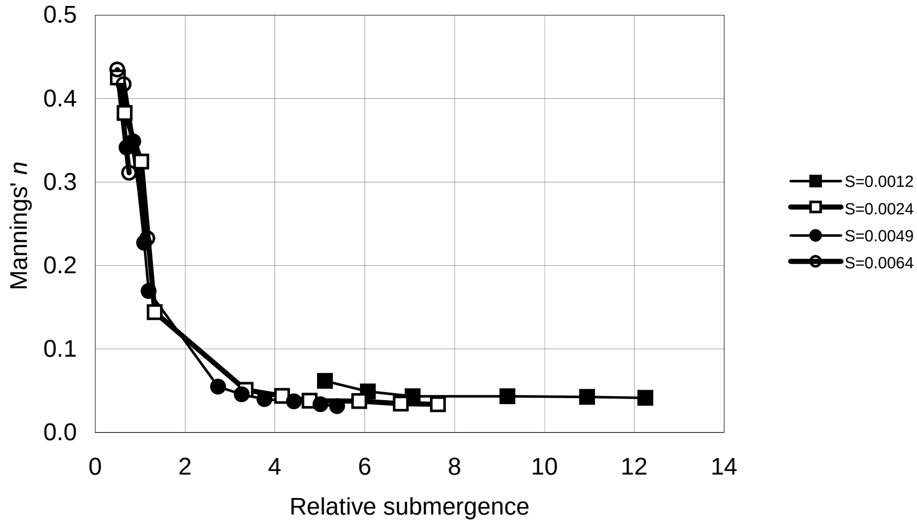

Figure 5.12 **Flow resistance in term of Manning's *n* variations with relative submergence at slopes of 0.0012, 0.0024, 0.0049 and 0.0064**

5.3 Conclusions

The laboratory experiments on hydraulics of low flows with large roughness elements were carried out to investigate the influence of roughness element densities and shape, and channel slopes on flow resistance. Experiments were performed with a wide range of relative submergence from 0.10 to 12.25. The results of the experiments showed that flow resistance expressed by Manning's *n* varies significantly with the flow depth for relative submergence less than 1, suggesting that Manning's equation is inappropriate for the condition where the resisting force primary arises from roughness element drag. It was also found that resistance depends strongly on roughness element density, while channel slope has little influence on resistance.

The results of the experiments on different shapes of roughness elements (cylinders and hemispheres) indicate that the shape has a significant influence on flow resistance for depths less than the height of the roughness elements. Values of Manning's *n* increase with increasing relative submergence up to 1 for roughness elements simulated by cylinders (Figs. 5.7 and 5.8), while its values decrease for the hemispheres (Fig. 5.12). This can be explained by difference in projected areas, which decrease with increasing flow depth for hemispheres, and remain constant for cylinders.

Chapter 6

RESISTANCE PREDICTIONS FOR STREAMS WITH LARGE-SCALE ROUGHNESS

6.1 Introduction

Laboratory experiments on flow resistance under large-scale and transitional-scale roughnesses have been described in Chapter 5. The influence of the roughness elements' density and shape (cylindrical and hemispherical) on flow resistance was observed under different hydraulic conditions determined by the discharge and bed slope. Graphical illustration of flow resistance was presented in terms of Manning's n resistance coefficient, which is widely used in practice (Figs 5.3, 5.7, 5.8 and 5.12). The results showed that Manning's n varies with flow depth, suggesting that the equation is unsuitable for use in its original form in cases of large-scale and intermediate-scale roughnesses.

Flow resistance over large-scale roughness has been studied by many researchers due to its importance in practical applications (e.g. Bathurst, 1981, 2002; Griffiths, 1981; Jarrett, 1984; Thorne and Zevenbergen, 1985; Lawrence, 1997; Smart et al, 2002). Three (large, intermediate, and small) roughness scales have been recognised (Bayazit, 1975; Bathurst, 1978). Furthermore, components of flow resistance as well as physical variables contributing to overall flow resistance have been documented (Bathurst, 1978, 1982; Bray and Davar, 1987; Lawrence, 1997, 2000). Various equations and resistance coefficients related to large-scale roughness have been developed (e.g. Jonker et al, 2001; Nikora et al, 2001; Stone and Shen, 2002). Some of them are very complicated and require comprehensive field data (Bathurst, 1978), while others are based on the relative submergence and require consideration only of the bed grain roughness (Bathurst, 2002; Jonker, 2001).

In most cases, development of the equations was based on laboratory or field data representing the large and intermediate roughness scales. For example, Bathurst (2002) proposed two new resistance relationships for $(8/f)^{0.5}$ (where f is Darcy-Weisbach friction factor) as functions of the relative submergence y/D_{84}. The relative submergence of his field data ranged from 0.37 to 11.4, covering all three roughness scales: large, small and intermediate.

Other investigations described three types of flow regime, viz. flows with high relative submergence, flow with small relative submergence, and flow over partially inundated rough bed (Lawrence, 1997; Lawrence, 2000; Nikora et al, 2001; Smart et al, 2002), and different modifications of Darcy-Weisbach friction factor *f* for application on appropriate condition were proposed.

We believe that modification of resistance coefficients such as Manning's *n*, the Chézy *C* and the Darcy-Weisbach *f*, which were developed for small roughness resistance, is not the only approach for predicting flow resistance under large and intermediate scales roughness conditions. Further analyses of the experimental data have therefore been performed, and new resistance methods for these conditions are proposed.

6.2 Proposed Methods

Flow resistance is a term used to describe the net effect of the forces driving and resisting the water movement, and is commonly represented by the ratio of the bed shear velocity to the mean flow velocity. When the flow depth, *y*, is four or more times the height of the bed material, *h*, the flow resistance can be considered to result from friction of the material forming the surface of the boundary, and can be described by well known friction coefficients such as the Chézy *C*, Manning's *n* and the Darcy-Weisbach *f*:

$$(V/V* = (8/f) = (C^2/g) = R^{1/3}/(gn^2) \qquad 6.1$$

When the channel bed material is large relative to the water depth (Fig. 6.1), the flow resistance is exerted by the roughness elements' drag rather than boundary shear, or friction.

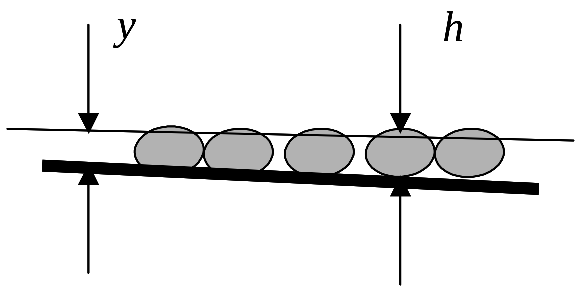

Figure 6.1 Large-scale roughness flow regime

Assuming that skin drag is not significant, the resisting force of *n* cylindrical roughness elements in the considered bed area is

$$F_d = \frac{1}{2} C_d \rho \overline{V}^2 \; n A_p \qquad 6.2$$

where A_p : projected cross-sectional area of the individual roughness element, given as

$$A_p = yD \qquad 6.3$$

where D :roughness element diameter

The weight component of the flow balanced by the resisting force under steady uniform flow conditions is given by

$$W = \gamma \; y \; S \; (A_t - n \; A_b) \qquad 6.4$$

where A_t :considered bed area,

n :number of roughness elements, and

A_b :base bed area of individual roughness element

Equating the weight component of the flow and the resisting force gives

$$V = \sqrt{\frac{2g}{C_d nD}\left(A_t - n \; A_b\right)} \sqrt{S} \qquad 6.5$$

Equation 6.5 can be written on more general form as

$$V = \frac{1}{F} \sqrt{S} \qquad 6.6$$

where F :resistance coefficient given by

$$F = \frac{1}{\sqrt{\frac{2g}{C_d nD} (A_t - n \; A_b)}} \qquad 6.7$$

Because the drag coefficient C_d depends on a number of variables such as the Froude number, the Reynolds number, the roughness element shape and the relative depth, estimating its value is not easy (Flammer et al, 1970). Furthermore, Lawrence (2000) found that experimental drag coefficient values were not only significantly higher than values estimated for an isolated cylinder and sphere in a free stream, but also exceeded reported values for free surface flows around isolated hemispheres. According to Lawrence, the drag coefficient varies significantly with relative submergence, *d/k* (Fig. 6.2), making it estimation difficult.

Estimation of C_d aside, it is debatable whether a drag type model in general is appropriate for these conditions (Smart, et al, 2002). To obviate the necessity for estimating C_d, experimental data were used to develop an approach for estimating the resistance coefficient *F* directly.

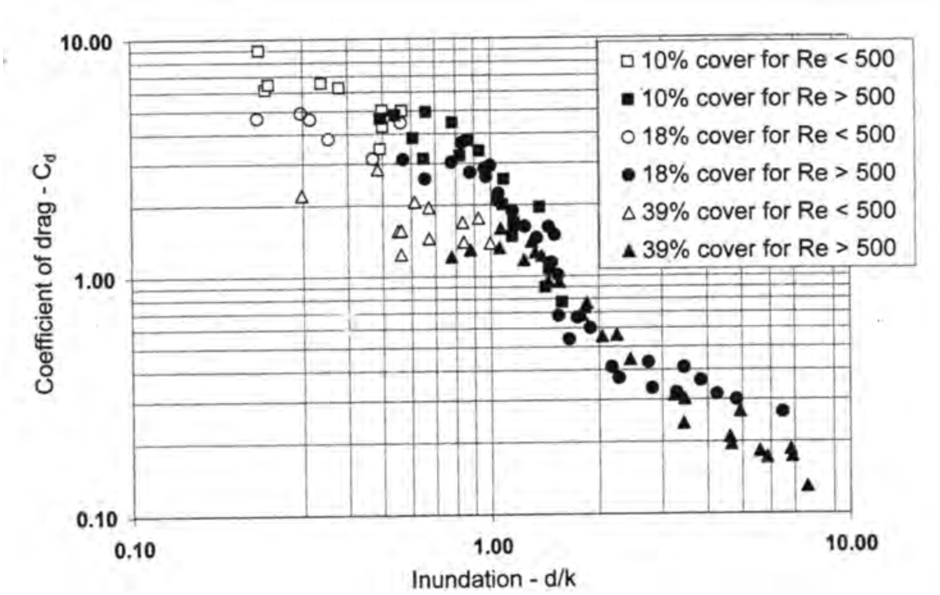

Figure 6.2 Element drag coefficients, classified by Reynolds number and percentage cover, calculated from observed data (Lawrence, 2000)

6.2.1 Approach for Estimation of the Resistance Coefficient *F* for the Large-Scale Condition

Flow resistance under the large-scale condition, where the flow depth is less than or equal to the height of the roughness elements is associated with very complex interaction between roughness element drag, wake vortices and local hydraulic jumps (Judd and Peterson, 1969). There is no known simple parameter for quantifying flow resistance under such complex conditions.

As a first step in the analysis, the basic variables contributing to flow resistance were defined and characterized as

- the concentration of roughness elements,
- the shape of roughness elements, and
- the spacing of roughness elements.

These variables were expressed in term of dimensionless parameters, the most suitable form found to be given by

$$F = f\left(\frac{W_{re}}{W_t}; \frac{A_p}{A_b}; \frac{WS_{re}}{A_t}\right) \qquad 6.8$$

where:

- The first parameter represents the roughness element concentration, and is expressed as the ratio of volume of roughness elements within the considered flow element W_{re} to the volume of the considered element W_t.
- The second parameter represents the roughness element shape, and is given as the ratio of horizontally projected cross-sectional area of the individual roughness element A_p to its base bed area A_b.
- The third parameter represents the roughness element spacing, as the ratio of the wetted surface of the roughness elements within the considered element WS_{re} to the considered plan area of the bed A_t.

The experimental data discussed in Ch. 5 that satisfied the large-scale condition were divided into two sets (Table 6.1 and 6.2). One set (Table 6.1) was used as the input variables data for a multiple regression analysis to develop the functional relationship (Eq. 6.8), while the other (Table 6.2) was used for verification of the proposed equation. Detailed experimental data are presented in Appendix.

Based on the experimental data (Table 6.1) the following equation was derived with r^2 equal to 0.936

$$F = \left(\frac{W_{re}}{W_t}\right)^{0.255} \left(\frac{A_p}{A_b}\right)^{-0.465} \left(\frac{WS_{re}}{A_t}\right)^{0.374} \qquad 6.9$$

Table 6.1 Experimental data used in the regression analysis

Test	Flow depth (m)	Discharge l/s	Density N/m	Slope	Flume bed
A7.1 – A7.5	0.019 – 0.084	0.48-3.59	5	0.00114	Smooth
B6.1 – B6.4	0.038 – 0.084	1.45-2.40	35	0.0045	Rough
B9.1 – B9.5	0.026 – 0.103	0.60-3.50	35	0.0073	Smooth
B10.1 – B10.3	0.020 – 0.064	0.26-0.75	59	0.0022	Rough
B13.1 – B13.4	0.026 – 0.085	0.30-1.35	59	0.0045	Smooth
C2.1 – C2.3	0.029 – 0.059	0.11-0.42	21	0.0024	Smooth

where N/m is number of roughness elements per meter length of the flume

The performance of the proposed equations (6.6) and (6.9) was assessed by comparison of measured and predicted resistance coefficients and velocities for the experiments listed in Table 6.2. Predicted and measured resistance coefficients and velocities as well as r^2 values are presented in Figs. 6.3 and 6.4. The average absolute errors and the standard deviations for these predictions are listed in Tables 6.3 and 6.4.

Table 6.2 Experimental data used for verification of equations (6.6) and (6.9)

Test	Flow depth (m)	Discharge l/s	Density N/flume L	Slope	Flume bed
A3.1 – A3.4	0.014 – 0.078	0.14-1.11	15	0.00057	Smooth
A5.1 – A5.5	0.021 – 0.066	0.64-2.76	15	0.0057	Smooth
A6.1 – A6.5	0.016 – 0.065	0.17-1.86	5	0.00057	Smooth
A8.1 – A8.5	0.010 – 0.068	0.51-5.64	5	0.0057	Smooth
B3.1 – b3.4	0.015 – 0.091	0.42-3.89	18	0.0045	Rough
B5.1 – B5.4	0.011 – 0.076	0.30-3.80	18	0.0073	Smooth
B8.1 – B8.5	0.015 – 0.097	0.25-2.50	35	0.0045	Smooth
B11.1 – B11.6	0.042 – 0.096	0.72-1.76	59	0.0045	Rough
B14.1 – B14.4	0.021 – 0.084	0.30-1.90	59	0.0073	Smooth
C3.1 – C3.2	0.040 – 0.048	0.32-0.42	21	0.0049	Smooth
C4.2. – C4.4	0.036 – 0.043	0.26-0.45	21	0.0064	Smooth

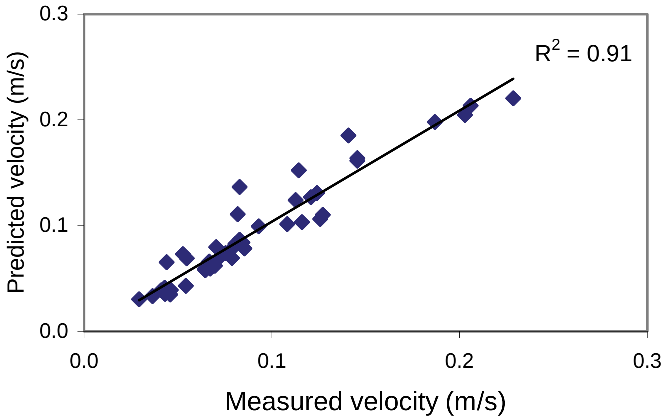

Figure 6.3 **Measured and predicted (by Eq.6.6) velocities for experiments listed in Table 6.2**

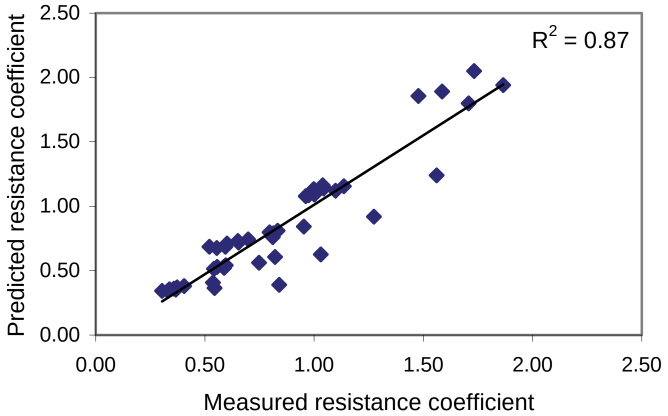

Figure 6.4 **Measured and predicted (by Eq.6.9) resistance coefficients for experiments listed in Table 6.2**

Table 6.3 **Velocity prediction errors in application of equation (6.6)**

	Tests										
	A3	**A5**	**A6**	**A8**	**B3**	**B5**	**B8**	**B11**	**B14**	**C3**	**C4**
Average Absolute Error (%)	13.48	10.51	16.60	9.12	14.01	30.30	11.77	10.26	9.47	10.66	13.27
Standard Deviation (%)	8.08	3.69	19.09	11.33	12.54	21.80	14.14	1.11	9.84	6.96	5.49

Table 6.4 **Resistance coefficient prediction errors in application of equation (6.9)**

	Tests										
	A3	**A5**	**A6**	**A8**	**B3**	**B5**	**B8**	**B11**	**B14**	**C3**	**C4**
Average Absolute Error (%)	16.56	11.77	13.03	7.54	11.32	21.26	9.27	11.45	8.34	16.03	12.36
Standard Deviation (%)	11.02	4.81	12.30	8.36	8.75	12.01	10.05	1.37	7.64	9.02	6.91

6.2.2 Approach for Estimation of Flow Resistance of Intermediate-Scale Roughness

The roughness is intermediate-scale if the relative submergence ratio of flow depth to roughness elements height, lies between one and four (Fig.6.5). This regime represents a state of flow in which the influence of the roughness elements on flow resistance is manifest as a combination of both element drag and boundary shear, or friction.

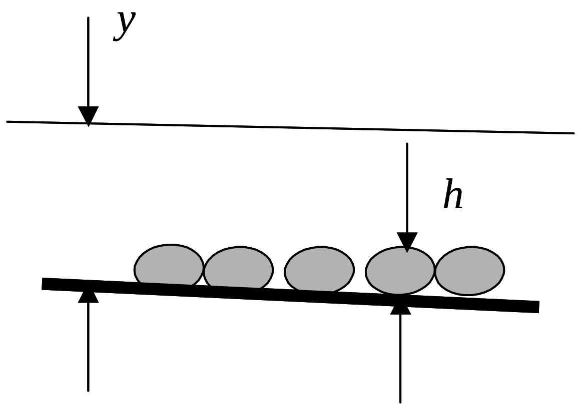

Figure 6.5 Intermediate –scale roughness flow regime

To estimate the flow resistance under such condition the following hypothesis was applied:

- If the relative submergence is equal or greater than four, then friction resistance dominates, and velocity can be estimated as

$$V = \frac{1}{n} R^{2/3} \sqrt{S} \tag{6.10}$$

- If the relative submergence is equal to or less than one, the drag effect of individual roughness elements on flow resistance will dominate and the proposed equation (6.6) should be used.
- As the relative submergence increases from one to four, the dominant resisting effect changes gradually from element drag to friction. The velocity can be estimated by

$$V = a \frac{1}{F} \sqrt{S} + (1 - a) \frac{1}{n} R^{2/3} \sqrt{S} \tag{6.11}$$

where *a* is coefficient related to the relative submergence. When the relative submergence is equal to one, the roughness is large-scale. In this case *a*=1 and equation (6.11) reduces to equation (6.6). When the relative submergence is four, the roughness is small-scale, and a becomes 0 to reduce equation (6.11) to equation (6.10).

Application of the proposed equation (6.11) requires specification of the coefficient a as a function of the relative submergence. A suitable relationship form was found to be the power function

$$a = b\left(\frac{y}{h}\right)^{c} \qquad 6.12$$

Appropriate data from the Series C experiments were used to determine values of b and c in equation (6.12), to yield

$$a = 1.125\left(\frac{y}{h}\right)^{-1.777} \qquad 6.13$$

The experimental values of coefficient a versus the relative submergence as well as the line of best correlation are shown in Fig. 6.6.

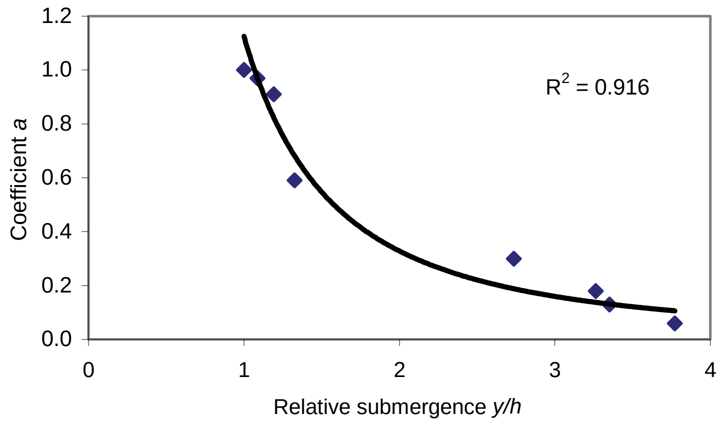

Figure 6.6 Line of best correlation the relative submergence and coefficient *a*

6.2.2.1 Verification of Proposed Equations (6.11) and (6.13)

The proposed equations (6.11) and (6.13) were verified by comparison of measured and predicted values of velocity for the Series B tests in the intermediate–scale roughness range, and some published experimental (Bathurst et al 1981) and field data (Griffiths, 1981; Bathurst, 1985).

Application of equation (6.11) required estimation of the resistance coefficients *F* and Manning's *n*. For the Series B tests, the resistance coefficients *F* were estimated for relative submergence equal to one for each element density using equation (6.9) and the following resistance coefficients were obtained:

- Density 1: F=0.51
- Density 2: F=0.77, and
- Density 3: F=1.07

For estimating Manning's *n* it was assumed that if the relative submergence is equal to or higher than four then one of the equations developed for Manning's *n* estimation can be used. For further verification of the proposed equation (6.11) an equation developed by Limerinos (1970) for Manning's *n* estimation was applied, i.e.

$$n = \frac{0.113\, R^{1/6}}{2.0 \log\left(R / D_{84} \right) + 1.16} \qquad 6.14$$

For the Series B experiments Manning's *n* value was calculated as 0.0405. Measured and predicted (Eq.6.11) velocities for Series B experiments (with y/h ranging from 1 to 2.2) together with the line of perfect prediction (PP) are plotted in Fig. 6.7.

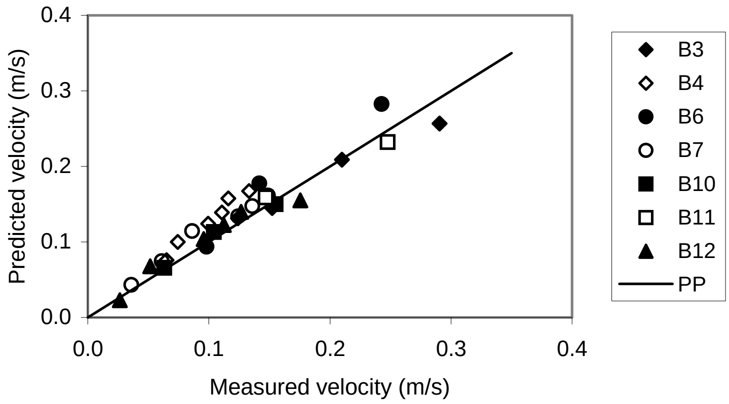

Figure 6.7 **Measured and predicted (Eq.6.11) for Series B experiments. The line of perfect prediction is indicated as PP.**

Average absolute errors as well as standard deviations for each of Series B experiment are listed in Table 6.5.

Table 6.5 **Velocity prediction errors in application of equations (6.11) and (6.13) to Series B experiments**

	Tests						
	B3	**B4**	**B6**	**B7**	**B10**	**B11**	**B12**
Average Absolute Error (%)	5.72	27.18	15.39	13.73	5.31	7.18	14.09
Standard Deviation (%)	3.98	6.52	8.57	10.40	2.54	0.88	7.90

Published experimental data of Bathurst (1981) were used for further verification of equations (6.11) and (6.13). Bathurst's experiments were performed in 9.54 m long and 1.168 m wide flume. Five different bed materials classified as 12.7, 19.05, 38.1, 50.8 and 63.5 mm were tested. These numbers are referring to the maximum size of each material. The D_{84} for each type of bed materials is given in Table 6.6. The values of Manning's n were estimated by equation (6.14), while values of the resistance coefficient F were obtained from the experimental data for a relative submergence of one. These are listed in Table 6.6.

Table 6.6 Estimated Manning's *n* and resistance coefficient *F*

Bed materials (mm)	D_{84} (mm)	Manning's *n*	Resistance coefficient *F*
12.7	7.8	0.0271	1.45
19.05	12.3	0.0294	0.98
38.1	27.0	0.0342	0.63
50.8	34.0	0.0359	0.60
63.5	44.0	0.0379	0.41

Measured and predicted velocities are plotted in Fig. 6.8.

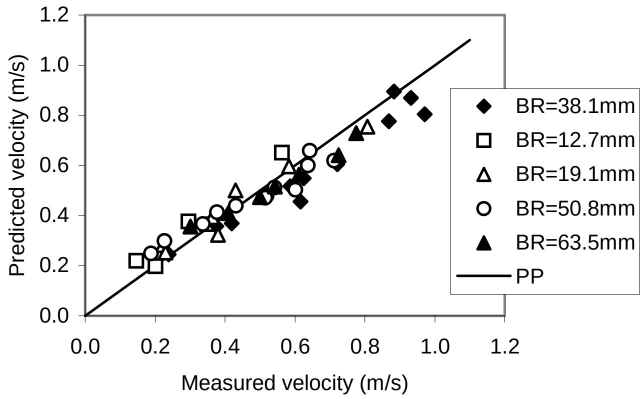

Figure 6.8 Measured and predicted velocities of Bathurst (1981) experiments

The average absolute errors and standard deviations for the predictions of Bathurst's (1981) result are given in Table 6.7.

Table 6.7 Velocity prediction errors in application of equations (6.11) and (6.13) to experiments data of Bathurst (1981)

	Bed Roughness (mm)				
	12.7	**19.05**	**38.1**	**50.8**	**63.5**
Average Absolute Error (%)	23.73	11.41	11.04	11.93	7.69
Standard Deviation (%)	18.07	7.45	6.83	9.62	5.29

The next step in the verification of the proposed equation (6.11) was performed using available field data (Griffiths, 1981; Bathurst, 1985). Data appropriate for the intermediate-scale roughness (11 sets field data of Griffiths (1981) and 12 sets field data of Bathurst (1985)) were selected and used for the verification. The same approach as for application of the experimental data was applied. Measured and predicted velocities as well as the line of perfect correlation are plotted in Fig. 6.9.

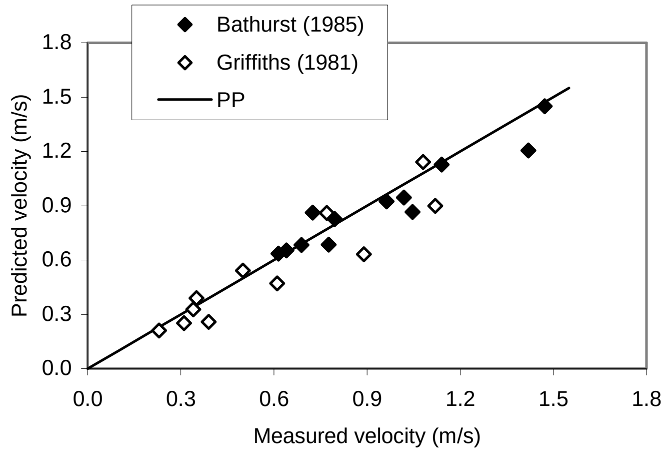

Figure 6.9 Measured and predicted (Eq.6.11) field data (Griffiths, 1981; Bathurst, 1985) velocities

Predicted average absolute errors and standard deviations for the field data predictions are listed in Table 6.8.

Table 6.8 Velocity prediction errors in application of equations (6.11) and (6.13) to field data of Griffiths (1981) and Bathurst (1985)

Data Source	Average Absolute Error (%)	Standard Deviation (%)
Griffiths (1981)	15.81	9.32
Bathurst (1985)	7.26	6.45

6.3 Conclusions

The results of the experimental work presented in Chapter 5 provided resources for development of an alternative approach for predicting flow resistance under large and intermediate-scale roughness conditions.

The form of equation (6.6) is proposed for predicting flow resistance under the complex large-scale roughness condition. Application of equation (6.6) requires estimation of the resistance coefficient *F*. Some of the experimental data that are related to the large-scale roughness condition were used for development of the resistance coefficient equation (6.9) as a function of three variables, while the others were used for the equations (6.6) and (6.9) verification. Average absolute errors and standard deviations of predicted resistance coefficients and flow velocities provide confirmation of suitability of the proposed equations.

Equation (6.11) provides a new way for estimating velocity under intermediate-scale roughness conditions. The equation incorporates the influence of both large- and small-scale roughness. Coefficient *a* (Eq.6.13) effects partitioning of the influence of the two roughness scales on flow resistance. The proposed equations (6.11) and (6.13) were applied to experimental (Bathurst et al, 1981) and field (Griffiths, 1981; Bathurst, 1985) data with promising results.

It is essential that for general application of the proposed equations (6.6) and (6.11) the following further investigation is required:

- Estimation of the resistance coefficient *F* as a simple function of the bed materials size.
- Further verification of the proposed coefficient *a*.

Chapter 7

Modelling river hydraulics for determination of the ecological Reserve

7.1 Introduction

The purpose of this project is to provide guidance for hydraulic analyses necessary to relate a flow regime, in terms of discharge, to biotic response in a river. Hydraulic analysis is necessary because biota do not respond to discharge per se, but rather to the hydraulic characteristics determined by the discharge together with the physical and vegetation characteristics of the river channel. In the course of recommending ecological flow requirements, changes in discharge need to be related to changes in hydraulic habitat.

At the outset to this chapter, it is important to define our use of the term “habitat”, since it is used in the literature in a range of contexts, which can be confusing. According to the American Fisheries Society, “habitat” is defined as the “specific type of place within an ecosystem occupied by an organism, population or community that contains both living and nonliving components with specific biological, chemical, and physical characteristics including the basic life requirements of food, water, and cover or shelter”. What is important about this definition is that it extends beyond the organism, species or population level to include communities, and it also applies to a specific type of place within an ecosystem. Their description for “habitat component” is the “single element (such as velocity, depth, or cover) of the habitat or area where an organism lives or occurs”. According to this definition, it is meaningful to refer to components of “habitat” such as “hydraulic habitat”, which is used in this chapter to denote hydraulic attributes of habitat which involve hydraulic parameters such as depth and velocity. This is consistent with terminology used internationally, eg. “habitat hydraulics” (Leclerc *et al*, 1996).

This chapter deals with the development and application of methods for improving the use of “standard hydraulic information” being applied in determinations of the ecological rivers Reserve (quantity) in South Africa. It constitutes an extension to hydraulic methods documented in the Building Block Methodology (BBM) manual (King *et al*, 2000), and the

Reserve documentation (DWAF, 1999; Birkhead, 2002). The ecological Reserve is defined as the water required to protect the aquatic ecosystems of the water resource, and refers to both quantity and quality as well as biota and habitat.

The overall aim of this project is to further develop the role of hydraulics in assessing ecological Reserves for rivers. This aim is expressed in the project proposal though four main objectives:

- provide hydraulic methods to link hydrologic river flow characteristics and biotic requirements,
- provide hydraulic methods for setting the Reserve when hydraulic data are limited,
- develop three-dimensional habitat modelling, and
- develop an index of hydraulic characteristics for quantifying habitat availability.

This chapter contributes to these four main project objectives, through

- the use of hydraulic indices defined by habitat-types for biota (Section 7.1),
- the use of hydraulic analyses coupled with digital terrain modelling and mapping of substrate and vegetation to compliment standard hydraulic information used in Reserve determinations (Section 7.2), and
- the development of software to assist hydraulic analyses and integration with other components of the ecological Reserve (Section 7.3).

7.2 Hydraulic Index

7.2.1 Background

The purpose of a "hydraulic index" is to provide a way of describing, in quantitative terms, the integrated hydraulic characteristics of a river reach, site or channel cross-section, in terms that are meaningful for ecologists to assess the response of the biota to changes in flow.

The need for an integrated hydraulic index was proposed at an ecological flow requirement (EFR) study for a site on the Thukela River (Kwazulu-Natal) in the late 1990s ("integrated" refers to the inclusion of important determinants of hydraulic habitat, such as for example depth, velocity and wetted perimeter for fish). The EFR approach used in the study was the BBM (refer to Chapter 2) – the most widely used method for assessing EFRs in South Africa. A workshop was held where the consequences of not meeting the recommended EFR were addressed, and the ecological consequences of providing alternative flow regimes (or scenarios) were considered. At this meeting, it became apparent that a quantitative means for assessing overall change in hydraulic habitat would be useful for determining the ecological impacts of different managed flow regimes. This is because there is no integrated index for expressing overall change in the type and abundance of hydraulic habitat.

Since the inception of this study, related projects have focussed attention on the development of methods for assessing the ecological consequences of managed flow regimes. Recently, an alternative holistic methodology, DRIFT (Downstream Response to Imposed Flow Transformations) (Brown and King, 2000) has been developed. It involves a scenario-based process for addressing the ecological and socio-economic consequences of progressive reductions in flows. The Flow Stressor-Response (FS-R) method has also been developed under the auspices of the Water Research Commission, and guides the evaluation of the ecological consequences of modified flow regimes using an index to score flow-related stress (O'Keeffe *et al*, 2002; O'Keeffe and Hughes, 2004). This method involves the scoring of indices that represent the "stress" response of biota to different flow regimes, through an assessment of hydraulic conditions. As such, the integration of the different determinants of hydraulic habitat is implicit in the method. This allows EFRs to be determined for different ecological categories (ECs).

This approach is more meaningful than pursuing an integrated "hydraulic index", since different biota (eg. fish and macroinvertebrates), communities and species respond to different constituents (eg. depth, velocity and wetted perimeter) of the hydraulic regime, and also at different spatial scales. An example of an index that has been widely used in the literature is the Froude number (a dimensionless index which is a function of depth and velocity) (eg. Jowett, 1993; Panfil and Jacobson, 1999). This and other indices (eg. Reynolds number) are dimensionless, and give no indication of absolute values of depth or velocity, and therefore cannot be used to assess the suitability of hydraulic habitat for biota. Therefore, the use of general hydraulic indices as surrogates for hydraulic habitat is limiting. It is also important that hydraulic habitat can be translated into biological (eg. general fish or macroinvertebrate) habitat. In this project, the role of hydraulics in providing relevant information to assist EFR determinations, within the context of existing and developing Reserve methods, is addressed.

7.2.2 Defining Habitat-Types for Use in Ecological Flow Assessments

The application of holistic methods for ecological flow determination (refer to Tharme, 1996) requires water requirements to be expressed as discharge rates (including its temporal characteristics) through assessments of the presence of suitable habitat for certain biota at different flows. The interface between the way in which flow requirements are assessed and expressed is through the results of hydraulic measurements, analyses and modelling of sites along rivers.

The primary product of these hydraulic analyses are relationships between discharge and the following determinants, which have been found over the course of numerous flow assessments, to be the most useful: depth (maximum and average), velocity (average), wetted perimeter, and width of the water surface. The discharge-depth (or rating) relationship is fundamental to hydraulic analysis, and is generally derived from a combination of measured and synthesized data (refer to Rowlston *et al* (2000) and Birkhead (2002) for descriptions of procedures for deriving hydraulic information for use in ecological flow requirements (or Reserves) in South Africa). Once the rating relationship for a river section has been developed, the relationships between discharge and the other hydraulic parameters (listed above) may readily be computed using the cross-sectional geometry.

Figure 7.1 is an example of a typical cross-sectional profile through a riffle, surveyed at a site on the Little Thukela River in Kwazulu-Natal (KZN). An example of a rating function developed for a cross-section through a rapid on the Mooi River (KZN) is plotted in Fig. 7.2, and Table 7.1 gives an example of hydraulic data extracted from the “look-up table” for the Mooi River site. The data in Table 7.1 can be plotted to provide graphical representation of the hydraulic determinants as a function of depth or discharge.

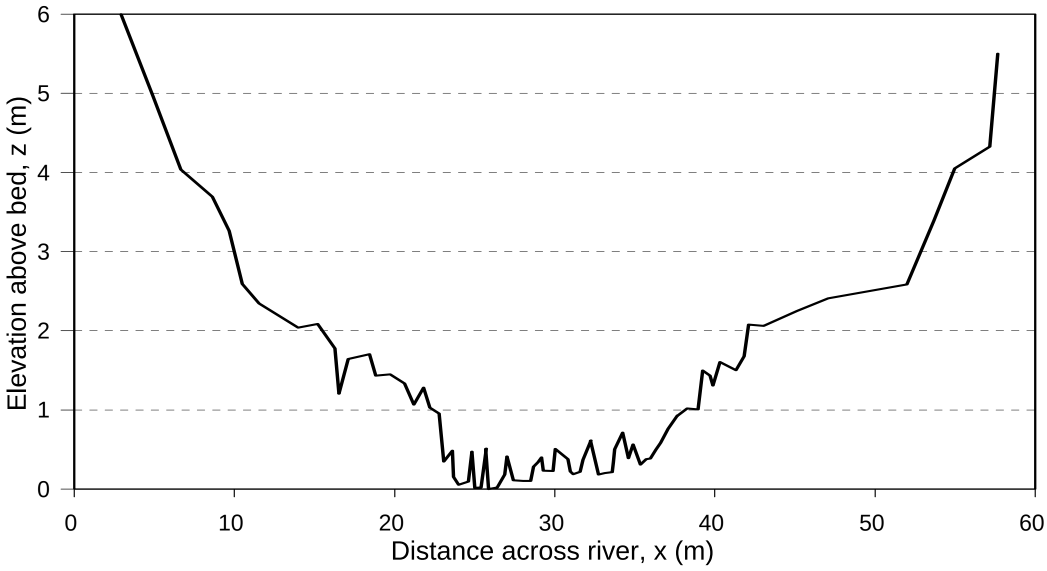

Figure 7.1 Example plot of a typical cross-section through a riffle

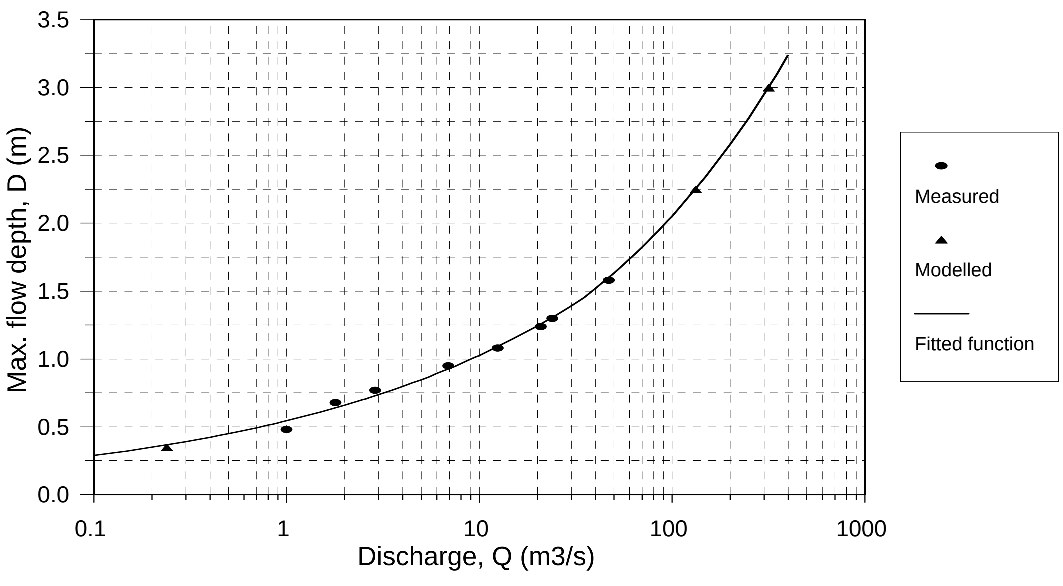

Figure 7.2 Example plot of a rating relationship on log-normal scale showing measured and modelled data and the fitted function

Table 7.1 Example of modelled hydraulic data for a cross-section provided by standard hydraulic analyses used in river Reserve studies

Maximum depth *H* (m)	Discharge *Q* (m^3/s)	Average depth $\overline{H}$ (m)	Area *A* (m^2)	Width *W* (m)	Perimeter *P* (m)	Average velocity *V* (m/s)
0.10	0.00	0.04	0.04	0.97	1.01	0.05
0.12	0.00	0.06	0.06	1.15	1.22	0.06
0.14	0.01	0.06	0.09	1.59	1.68	0.08
0.16	0.01	0.05	0.13	2.86	2.99	0.09
0.18	0.02	0.05	0.20	3.81	4.01	0.09
0.20	0.03	0.06	0.29	4.73	5.02	0.09
0.22	0.04	0.07	0.39	5.65	6.04	0.09
0.24	0.05	0.08	0.51	6.15	6.68	0.10
0.26	0.07	0.09	0.64	6.84	7.51	0.11
0.28	0.09	0.10	0.78	7.52	8.34	0.11
0.30	0.11	0.11	0.94	8.35	9.33	0.12
0.32	0.14	0.12	1.12	9.70	10.82	0.13
0.34	0.18	0.12	1.33	10.67	11.93	0.14
0.36	0.22	0.13	1.55	11.72	13.15	0.14
0.38	0.27	0.12	1.83	15.43	17.03	0.15
0.40	0.32	0.13	2.14	16.12	17.89	0.15

Maximum depth (*H*) is defined as the elevation difference between the lowest point in the channel cross-section and the water surface, whereas the average depth ($\overline{H}$) is given by the ratio of cross-sectional flow area (A) to water surface width (*W*).

Figures 7.1 and 7.2 and Table 7.1 comprise the "standard hydraulic data" that are used in Reserve determinations in South Africa at the Rapid III, Intermediate and Comprehensive levels. From a hydraulics perspective, the main difference between these three levels of Reserve assessment lies in the quantity of rating data that are measured at river sites: one, two and four data sets are generally collected for Rapid III, Intermediate, and Comprehensive assessments, respectively. The proportion of measured and synthesized rating data (see Fig. 7.2) determines the confidence in the fitted rating function and resulting hydraulic characterisation (Table 7.1). For Intermediate and Comprehensive assessments, there may also be opportunities to survey and rate multiple cross-sectional profiles through different morphological features (ie. rapids/riffles, runs and pools). These features provide different hydraulic habitat, particularly with respect to velocity and depth - the main determinants used by Kleynhans (1999) to define hydraulic habitat for fish, described in the following section.

In Reserve determinations, ecologists use the "standard hydraulic data" (ie. Figs 7.1 and 7.2 and Table 7.1), with the aid of on-site assessments, photographs and video exposure, to determine the quantity and quality of hydraulic habitat at different flows. It requires substantial experience and interpretation to provide assessments of site- and reach-based biological habitats using a cross-sectional survey/s and the results of one-dimensional hydraulic analyses (biological habitat refers to the integration of the components defining habitat (eg. hydraulic, substrate and cover attributes for fish)). This section describes a procedure for using standard hydraulic information as the basis for quantifying hydraulic habitat. This will allow assessments of abundance and suitability of hydraulic habitat to be applied more consistently in Reserve determinations.

7.2.2.1 Defining Hydraulic Habitats for Fish

Kleynhans (1999) suggested that the hydraulic information necessary to characterize habitat for fish is depth-averaged velocity (V) and flow depth (D). Together with substrate and vegetation cover information, these are sufficient to broadly describe fish habitat. Further, he suggests that velocity and depth need only be specified coarsely, and has proposed the following four velocity-depth classes (hydraulic habitat types), as adapted from Oswood and Barber (1982):

- *Slow (<0.3 m/s) and shallow (<0.5 m)*: This includes shallow pools and backwaters.
- *Slow (<0.3 m/s) and deep (>0.5m)*: This includes deep pools and backwaters.
- *Fast (>0.3 m/s) and shallow (<0.3 m)*: Shallow runs, rapids and riffles fall in this class
- *Fast (>0.3 m/s) and deep (>0.3 m)*: Deep runs, rapids and riffles fall under this class.

A graphical representation of the velocity-depth domain and its division into four classes is provided in Fig. 7.3.

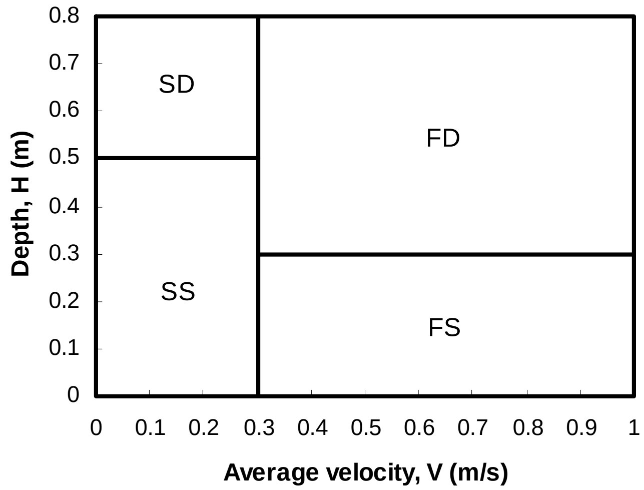

Figure 7.3 Kleynhans (1999) hydraulic habitat descriptions for fish (SS=slow and shallow, SD=slow and deep, FS= fast and shallow, FD=fast and deep). The velocity and depth axes are truncated for plotting purposes at 0.8 and 1.0, respectively

For each velocity-depth class, the presence of features that provide cover for fish (ie. refuge from high velocity, predators, high temperatures, etc) are also taken into consideration (Kleynhans, 1999). These features include:

- *Overhanging vegetation*: thick vegetation overhanging water by approximately 0.3 m and not more than 0.1 m above the water surface. This includes marginal vegetation.
- *Undercut banks and root wads*: banks overhanging water by approximately 0.3 m and not more than 0.1 m above the water surface.
- *Stream substrate*: various substrate components (rocks, boulders, cobbles, gravel, sand, fine sediment and woody debris “snags”) that provide cover for fish.
- *Aquatic macrophytes*: submerged and emergent water plants.
- *Water column*: used to assess depth in relation to the size of fish.

Irrespective of the ecological flow method applied, holistic methods require an assessment of the suitability of different hydraulic habitats for biota over a range of discharges. In the application of the BBM in South Africa over the past decade, cross-sectional profiles (eg. Fig. 7.1) and the results of standard hydraulic analyses (eg. Table 7.1), complimented with photographic information, have been used to characterise hydraulic habitat. The velocity-depth descriptions and associated substrate and cover features provide a broad categorisation of hydraulic habitats for fish. The presence of these hydraulic habitat types may be quantified using a relative abundance scale with associated proportional percentage occurrence, an example of which is given in Table 7.2 (adapted from Rankin, 1995).

Table 7.2 Abundance scoring of habitat types for fish

Descriptor	Score	Occurrence (%)
None	0	0
Rare	1	0-5
Sparse	2	5-25
Moderate	3	25-75
Abundant	4	75-90
Very abundant	5	90-100

7.2.2.1.1 Application of Hydraulic Habitats for Fish to Laboratory Flume Data

The hydraulic habitat description of Kleynhans (1999) is applied here to the most simple case of steady, uniform flow in a prismatic rectangular channel. In their investigations of the influence of instream vegetation on hydraulics, James *et al* (2001) conducted laboratory experiments in a 1.0 m wide channel on a slope of 0.001. Two of their conditions are considered here: the basic channel with no vegetation, and this channel with 0.25 m strips of simulated emergent vegetation along each bank. For each of these channels, stage-discharge and transverse distributions of depth-averaged velocity were measured. For the purpose of this illustration, the laboratory channels are considered as models of 3.0 m wide real channels, and the measurements are scaled up according to the Froude law. The hydraulic habitat is considered for two common discharge values (prototype values of 0.078 m^3/s and 0.23 m^3/s).

Using the hydraulic biotope approach, the flow conditions in both these channels for both discharges would be classified as “runs”. The hydraulic indices proposed by Rowntree and Wadeson (1998) are listed in Table 7.3. (A value of equivalent bed roughness appropriate for the concrete lining of the laboratory channels is assumed, ie. k_s = 0.15 mm. For the vegetated channel, only the clear channel flow area is considered.)

Table 7.3 Hydraulic biotope indices for example channels

Hydraulic index	Discharge (m^3/s)			
	Basic channel		Vegetated channel	
	0.078	0.23	0.078	0.23
Fr	0.56	0.59	0.46	0.35
V/H	7.2	5.3	4.2	2.1
Re	25800	76800	51700	153900
u_*	0.024	0.034	0.033	0.051
Re^*	3.7	5.1	5.0	7.7

The value of the information given in Table 7.3 for inferring suitability of hydraulic habitat is not immediately apparent.

The same two channels have been analysed using the hydraulic habitat types proposed by Kleynhans (1999), graphically represented in Fig. 7.3. Using cross-section average measurements, and again only considering the clear width of the vegetated channel, the relevant indicators and classification is shown in Table 7.4. These conditions are plotted on the classification diagram in Fig. 7.4

Table 7.4 Kleynhans (1999) classification for example channels (cross-section average values)

Indicator	Basic Channel		Vegetated Channel	
	Q = 0.078 m^3/s	Q = 0.23 m^3/s	Q = 0.078 m^3/s	Q = 0.23 m^3/s
V (m/s)	0.43	0.64	0.47	0.57
H (m)	0.06	0.12	0.11	0.27
Hydraulic habitat type	FS	FS	FS	FS

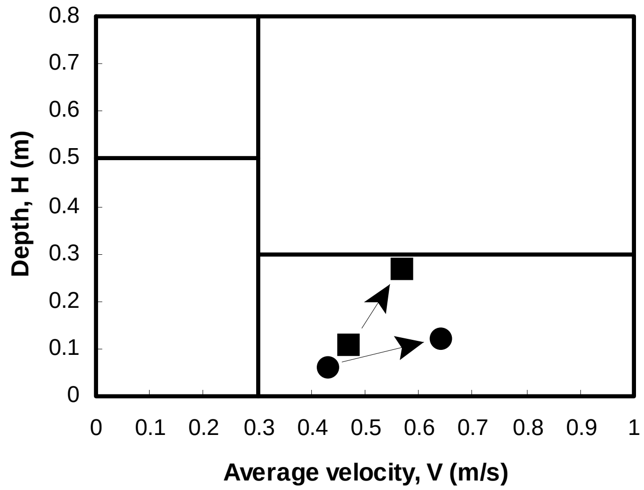

Figure 7.4 Hydraulic habitat classification for example channels, using cross-section average parameters (circles are for the basic channel, squares for the vegetated channel)

Presentation of the channel hydraulics in terms of hydraulic categories is clearly more useful for ecological interpretation of biological habitats than the hydraulic biotopes. Although the category is FS for both channels and both discharges, it is useful to be able to see on the diagram how close the conditions are to the category boundaries. It is also clear from Fig. 7.4 that the channels respond differently to an increase in discharge: the vegetated channel accommodates the increase mainly by increasing flow depth, whereas the unvegetated channel responds mainly by increasing velocity, as indicated by the arrows.

A further advantage of the hydraulic habitat classification is that it can be applied with different levels of data or analysis resolution. In the example cases, transverse distributions of depth-averaged velocity were measured. It is therefore possible for different flow categories to be defined in the same cross-section (or reach). Using the measured data, the range of conditions for each channel are plotted in Fig. 7.5.

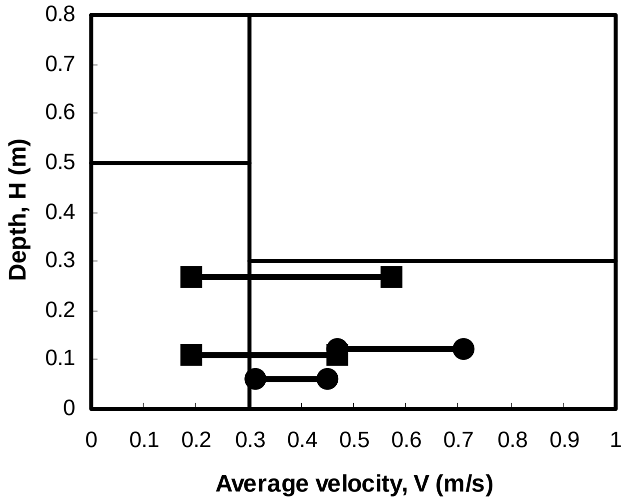

Figure 7.5 Hydraulic habitat classification for example channels, using cross-section varying parameters (circles are for the basic channel, squares for the vegetated channel)

Figure 7.5 shows the variation of ecologically relevant flow conditions across the channel, and shows that the edge vegetation induces a different hydraulic habitat category (SS). This information provides a more complete definition of hydraulic habitat that is not available from the cross-section average analysis, and would not be apparent in a hydraulic biotope description.

Depending on the data available, or the level of hydraulic analysis, the relative extents of the different conditions can be described by bar graphs in terms of channel width (or area for a reach) and the hydraulic habitat categories. Bar graphs for the unvegetated and vegetated channels are shown in Fig. 7.6 for the lower discharge (0.078 m^3/s) and in Fig. 7.7 for the higher discharge (0.23 m^3/s).

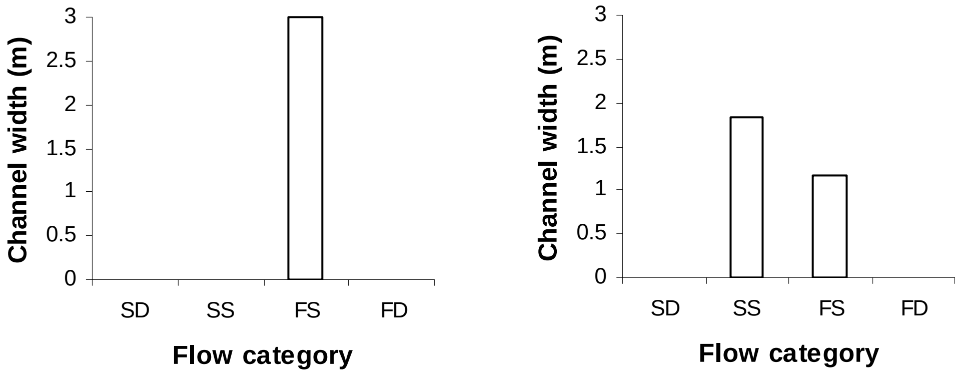

Figure 7.6 Distributions of flow conditions for the basic channel (left) and vegetated channel (right) for discharge of 0.078 m^3/s

The width in category SS for the vegetated channel shown in Fig. 7.6 includes the vegetated strips. These can be excluded if only the clear channel width is to be considered; Fig. 7.7 presents the bar graphs for the clear channel width only, for the two discharges.

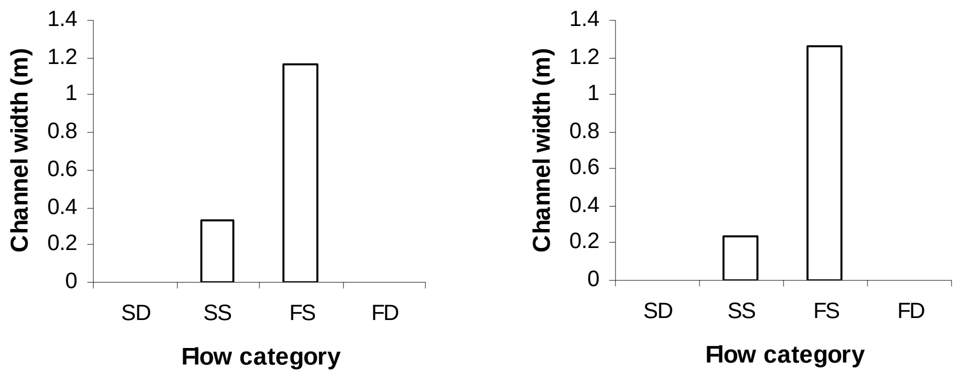

Figure 7.7 Distributions of flow conditions for the clear width of the vegetated channel for discharges of 0.078 m^3/s (left) and 0.23 m^3/s (right)

So far, the hydraulic conditions have been defined for two resolution levels, cross-section average conditions and conditions varying over the cross section. The classification can also be done over a reach of channel if sufficient data are collected, or an appropriate hydraulic analysis is carried out (refer to Section 7.3 describing three-dimensional spatial modelling. In Section 7.2.3 (following), hydraulic models are used to predict typical velocity distributions as well as the distribution of depth across representative surveyed cross-sections. This provides the means to estimate not only the range of depth and velocity values, but also the proportion of hydraulic habitat falling within the different categories. Three-dimensional spatial modelling (Section 7.3) allows the extent of inundation within a surveyed area to be visualised, and the connectivity of areas of varying depth to be determined.

The examples presented here represent the simplest possible hydraulic environment in a river – steady uniform flow in a prismatic channel reach, or a "run" in hydraulic biotope terms. Obviously, more complex situations have to be quantified in Reserve determination studies, but similar representations can be used. It is the hydraulic analysis that presents the major difficulty, as data are unlikely to be available for all conditions required. Different flow conditions require different analysis approaches. The cross-section average cases presented would use one-dimensional uniform or gradually varied flow techniques, which are fairly straight forward for relatively deep flows. "Uniform" flow where the substrate elements are large compared with the flow depth is still not predictable with adequate reliability. Description of the transverse velocity distribution would require two-dimensional turbulence modelling (a not inconsiderable challenge) or some form of integration of modelling or higher resolution empirical results. Variations in velocity associated with channel irregularities and obstructions present additional complications of this type. The other hydraulic biotopes introduce increasing complexity requiring, in addition, rapidly varied flow analysis in one or two dimensions. Hydraulic biotopes may be useful for identifying the flow type in order to specify the type of hydraulic analysis required, but cannot on their own provide a meaningful, quantitative description of hydraulic characteristics. They also appear to be used to classify observed conditions – their prediction for unobserved situations would require detailed hydraulic analysis anyway.

7.2.2.1.2 Using Hydraulic Habitats in the Determination of Ecological Flows for Fish within the Framework of the H-FS-R Methodology

A method has been developed for applying the concept of hydraulic habitat types (or classes) in the determination of ecological flows for fish using the HFSR methodology. It differs from the original FS-R method (O'Keeffe *et al*, 2002; O'Keeffe and Hughes, 2004) in that the hydraulic habitat is interpreted in terms of biological habitat requirements (eg. fish), and should preferably be referred to the Habitat-Flow Stressor-Response (H-FS-R) method. It is a "working method", and will benefit from future development and refinement by applied research and during the course of ecological Reserve assessments. The procedure is presented here with the purpose of clearly describing the role of hydraulics. This is necessary, since application and further development of hydraulic methods for the Reserve necessitate an appreciation and understanding of hydraulic information, scale and resolution requirements. Standard hydraulic analyses for the ecological Reserve are based on one-dimensional hydraulic modelling (eg. Table 7.1). Often, these inadequately meet the hydraulic information requirements for ecological assessments, particularly for fish and macroinvertebrates. Three-dimensional spatial modelling assists, to a certain extent, by providing inundation patterns (extent and depth) over a larger area of river site than may be achieved using standard cross-sectional surveys (refer to Section 7.3). There is therefore a need to re-examine the role of hydraulics in the flow assessment for fish, which applies an integrated assessment of hydraulic habitat through the use of different habitat types. These types are defined using two basic hydraulic parameters: depth and velocity. Water surface width is also included as a river scaling factor.

The procedure (described below) has been developed within the context of the H-FS-R ecological flow assessment methodology. It is also applicable for use in other holistic flow determination methods (eg. DRIFT) that require a quantitative assessment of habitat suitability and abundance.

The method has been divided into a four-step procedure:

1 Determination of on-site " flow – habitat type abundance"

The first step in the method is the on-site scoring of the four habitat types defined for fish (refer to Section 7.2.2.1), taking cognisance of the substrate, cover and water column features provided by the river site. The reason for use of the term "flow" rather than "discharge" in "*flow - habitat type abundance*" is to differentiate between this on-site semi-qualitative assessment and *Step 4* of the procedure, where discharge is explicitly incorporated through hydraulic analysis. The on-site assessment is best undertaken jointly by the hydraulician and fish ecologist, since it provides an opportunity for the specialists to develop an appreciation and understanding of relevant influences from the related disciplines. Secondly, the hydraulician is required to collect hydraulic data during the course of assessment studies, and it would be valuable to provide habitat type abundance scorings for each of these (since they are associated with a measured discharge rate). Although this assessment involves subjectivity, it provides a valuable source of information to compliment the abundance scorings of hydraulic habitat type from more quantitative methods, described later (refer to Section 7.2.3). The abundance scorings are adjusted according to the river scale, since depending on the size of a river, a site with a low proportion of certain habitat types may still provide substantial absolute habitat. This is addressed by taking account of the channel width, and adjusting the abundance ratings if necessary.

2 Determination of on-site "stress response to habitat type"

Habitat suitabilities for a particular species (ie. with reference to the preferences and requirements of a "target" species such as rheophilic species requiring fast flowing water during their whole life-cycle) are rated on the basis of specialist knowledge, based on a simplified habitat suitability index proposed by Stuber, Gebhart and Maughan (1982). This method makes use of the suitability of various habitat characteristics to fulfil the life-stage requirements of the "target" species. The suitability of the observed habitat (velocity-depth class, substrate and cover) under known flow conditions (measured discharge) is scored for each of the following components using the scoring system given in Table 7.5.

- Breeding (*B*)
- Survival and abundance (*S*)
- Cover (*C*)
- Health (*H*)
- Water quality (*W*) (flow related aspects – temperature and oxygen concentration)

Table 7.5 Suitability scoring

Suitability descriptor	Score
None	0
Poor	1
Low	2
Moderate	3
High	4
Very high	5

Habitat suitabilities for a particular species or group of species are based on a simplified index (HSI), given by equation 7.1. The index is calculated as an average value of the above five components, transformed and expressed in the range ten to zero for compatibility with the stress index used in the FS-R methodology (ie. 10 indicates completely unsuitable conditions and 0 denotes highly suitable conditions).

$$HSI = 10(1 - \frac{B + S + C + H + W}{25}) \qquad 7.1$$

Where an assessment is done outside the breeding season (dry season), the HSI may be calculated by excluding suitability for breeding requirements (ie. neglecting the breading component of the life-stage, and replacing 25 in equation 7.1 with 20).

A habitat suitability index is determined for each observed flow at a river site, and represents the habitat stress response index for an observed (measured) discharge (refer to Table 7.7). Although the HSI requires a certain level of specialist knowledge and judgement, it is based on abundance scoring of habitat suitability classes through observation (*step 1*) and an assessment of species stress response (through the HSI in *step 2*) after fish sampling. This is valuable, since much of the remaining assessment of habitat abundance relies on modelled hydraulic data and photographic information. The assessments from *step 1* and *step 2* are used to populate a row of data in Table 7.7 corresponding to a measured discharge (shaded row corresponding to a habitat index of 6). The on-site assessment of habitat type abundance (*step 1*) may be refined during the ecological workshop where more quantitative hydraulic information is available (eg. Table 7.1 and Section 7.2.3).

3 Development of generic "habitat type abundance - population stress response"

Step 3 of the procedure involves the development of generic habitat type abundance and population stress response information, an example of which is provided in Table 7.6. The species or group response is rated by considering how various hydraulic habitats and features (integrated into a single habitat index score) fulfil various life-stage requirements (listed in *step 2*). The response scorings (in terms of abundance – adapted from O'Keefe *et al*, 2002) will vary, since the suitability of habitats differs for different species or groups (eg. rheophilic, semi-rheophilic or limnophilic). This information provides the link between "discharge – hydraulic habitat type abundance" information (derived from modelled data - refer to Section 7.2.3) and "stress response" required for application of the H-FS-R methodology. This information should also be used, however, to confirm agreement of on-site assessments made in *steps 1* and *2*, thereby assisting with the refinement of this generic stress response information. The generic tables require refinement to ensure that potential combinations of abundance scores for the different habitat types are adequately covered (refer to *step 4* for a discussion of the assemblage of habitat abundance ratings).

Table 7.6 Example of a generic habitat type abundance and population stress response table for a semi-rheophilic species

Depth-velocity index	**Abundance of hydraulic habitat suitability class**				**Total abundance score**	**Target species/group**	
	FD	**FS**	**SD**	**SS**		**Response ito abundance[1]**	**Species/group stress**
0	5	5	5	5	20	All very abundant	0
1	4	5	5	5	19	All very abundant	0
2	4	4	5	5	18	All very abundant	0
3	3	4	5	5	17	Abundant	1
4	2	3	5	5	15	Abundant	1
5	2	2	4	5	13	Moderate	3
6	1	2	3	4	10	Moderate	3
7	0	2	2	3	7	Low	4
8	0	1	1	2	4	Low	5
9	0	0	0	1	1	Rare	8
10	0	0	0	0	0	None	10

[1] refer to O'Keefe *et al* (2002) for descriptions of changes in abundance applied in the FS-R approach

4 Integrating "discharge – habitat type" and "habitat type - stress response"

The final step in the four-step method is the preparation of an integrated table (Table 7.7) linking discharge to stress response through the rating of habitat type suitability (provided by the different classes) and abundance. Habitat type abundances (including substrate and cover features) are scored on-site in *step 1* (shaded row in Table 7.7). Stress response indices are, however, required for a range of discharges, and the remaining habitat type abundance scores are derived from modelled hydraulics (discussed in Section 7.2.2).

Table 7.7 Example of an integrated matrix linking limnophilic species stress to discharge through the assessment of abundance of different habitat suitability classes (*step 1 and section 7.2.2*) and generic abundance and population stress for a target group or species (*step 3*)

Habitat index	Abundance of habitat suitability class				Target species/group		Discharge (m^3/s)
	FD	FS	SD	SS	Response ito abundance	Species/group stress	
0	5	5	5	5	All very abundant	0	
1	4	5	5	5	All very abundant	0	
2	4	4	5	5	All very abundant	0	
3	3	4	5	5	All very abundant	0	
4	2	3	5	5	All very abundant	2	1.0
5	2	2	4	5	Abundant	3	0.36
6	1	2	3	4	Moderate	4	0.17[1]
7	0	2	2	3	Low	6	0.10
8	0	1	1	2	Low	7	0.05
9	0	0	0	1	Rare	9	0
10	0	0	0	0	None	10	0

[1] measured discharge during on-site assessments of habitat type abundance (*step 1*) and related species/group response (abundance and stress) (*step 2*)

In flow assessments, rheophilic species (requiring fast flows for all stages of their life-cycle) have often been used as an indicator group, and their requirements have generally been found to dominate the habitat-stress response. Nevertheless, the range of flows considered must allow all possible assemblages of potentially suitable fish habitats to be quantified. This is because different species or groups have different habitat requirements, and it is necessary to cover the overall requirements of the fish community or assemblage. For this reason, it may be necessary to define "discharge - stress responses" (ie. Table 7.7) for different target species or groups having different habitat suitabilities.

At particular river sites, optimum habitat conditions for each of the defined habitat types may not occur simultaneously (ie. very abundant score for velocity-depth class and substrate/cover features), since the presence of certain habitat types changes at the expense of others. This is the case in uniform prismatic channels that display low habitat diversity, whereas hydraulically complex channel morphologies are likely to be characterised by a suite of habitat types over a range of flows. The relative abundance of habitat types is therefore a function of discharge, local morphology and vegetation.

The species stress-discharge values from Table 7.7 are subsequently used in the H-FS-R method to define stress-duration curves for different flow regimes as discussed by O'Keeffe *et al* (2002) and O'Keeffe and Hughes (2004).

7.2.2.2 Defining Habitat for Macroinvertebrates[1]

The method for determining the stress response of macroinvertebrates to habitat condition (using the H-FS-R method) is in the early stages of development and is less sophisticated than that described for fish. It is nevertheless useful to refer here to aspects of the method, particularly the proposed habitat-type categories, for the purpose of defining the hydraulic information requirements.

The main parameter used in the classification of macroinvertebrate hydraulic habitat is depth-averaged velocity. This, together with substrate type and vegetation, may be used to broadly describe macroinvertebrate habitat. Two of the proposed habitat type definitions are modifications of the well-known macroinvertebrate-based biotope classifications: "Stones in Current" (SIC) and "Stones out of Current" (SOC). These definitions originate from the SASS (South African Scoring System) index for broadly assessing river condition on the basis of the sensitivity of macroinvertebrate families present at a site. These biotope definitions are not particularly meaningful from hydraulics (ie. use of the term "current") or geomorphological (ie. use of the word "stones") perspectives, and have therefore been modified. The proposed five habitat type classifications are:

- *SCS: Slow (< 0.3 m/s) flow over/around Coarse Sediments (size > 16mm) and bedrock*
- *FCS: Fast (> 0.3 m/s) flow over/around Coarse Sediments (size > 16 mm) and bedrock*

[1] based on material provided by and discussions with Ms Christa Thirion (Resource Quality Services, Department of Water Affairs and Forestry) and Dr Mandy Uys (Laughing Waters)

The SIC and SOC substrate classifications have been modified to include substrates other than gravels (equivalent of “stones” in the original biotope classification), although it is recognised that large gravel and loose cobbles generally provide better substrate habitat than boulders and bedrock for rheophilic taxa. Un-embedded sediments with interstitial spaces also provide superior quality habitat than embedded sediments. The quality of substrate provided by submerged and emergent (partially submerged) coarse sediments also differs, and relative flow depth therefore needs to be taken into account when evaluating the suitability of these two habitat types.

- *SV: Slow (< 0.3 m/s) flow through Vegetation*
- *FV: Fast (> 0.3 m/s) flow through Vegetation*

These two habitat types include both fringing and aquatic vegetation. Leafy vegetation is recognised as providing more suitable habitat for vegetation-dwelling taxa than, for example, sedges or reed stems.

- *SFS: Slow (< 0.3 m/s) flow over Fine Sediments (size < 16mm)*

This habitat type includes sediments ranging from clays and silt to gravels. The abrasive action of mobile sediments (particularly sand) reduces the quality of this habitat type for target macroinvertebrate taxa.

The presence of these habitat types for macroinvertebrate fauna are rated using the relative abundance scoring system developed for fish (refer to Table 7.2). These “presence” ratings also account for the suitability (or quality) of each of these broadly defined classes, by incorporating additional considerations, as previously described.

The procedure applying these macroinvertebrate habitat types within the FS-R method (i.e. H-FS-R) is similar to the four-step method described for fish (in Section 7.2.2.1.2). The first two steps involve on-site evaluations of (*1*) “*flow-habitat type abundance*” and (*2*) “*stress-response to habitat type*”. Generic relationships between habitat type and population stress have not been developed for target macroinvertebrate taxa (Step *3*), and is therefore not yet included. Step *4* involves the integration of “*discharge-habitat type*” and “*habitat type-stress response*” using hydraulic analyses to provide relevant hydraulic habitat information (eg.

velocity distributions and wetted perimeter) for a range of discharges. Surface width or wetted perimeter are useful determinants of absolute river size, and are used for assessing the available quantity of habitat type.

The proposed habitat types have been classified hydraulically using only velocity, with depth incorporated through relative submergence of coarse substrates and bedrock (FCS and SCF categories). A threshold velocity of 0.3 m/s is used to distinguish between slow and fast flow, and additional divisions of these categories may be required, eg. very slow (< 0.1 m/s) and very fast (> 0.6 m/s). These velocity classes will require refinement based on future development and testing. Velocity is defined by cross-sectional average values, recognising that the spatial distribution of velocity is complex and highly variable in rivers characterised by large relative roughness. These distributions are being studied as part of a related project (WRC Project no. K5/1405). Although standard hydraulic analyses for Reserve determinations provide only estimates of average velocity, methods for predicting typical spatial probability-distributions are presented in the following section (Section 7.2.3.2). These methods provide valuable information, since the boundaries used to define velocity classes (ie. slow, fast, etc.) becomes less important when the spatial distribution of velocity is known or can be estimated.

7.2.3 Deriving Semi-Quantitative Hydraulic Habitat Information

Riverine biota including fish, macroinvertebrates and vegetation display strong preferences for certain values of water depth, velocity, and bed shear stress, or combinations of these hydraulic variables (Lamouroux, 1998). Hydraulic descriptions used by ecologists differ from traditional hydraulic applications: river biota responds to sets of point hydraulic variables, whereas traditional hydraulic engineering has been concerned with larger spatial scales (eg. flood analyses). Modelling point hydraulic variables in river reaches at low-flows with large resistance elements using high resolution multi-dimensional hydraulic modelling is imprecise and requires accurate topographical information (Lamouroux, 1998). An alternative method for providing this information is by modelling characteristic spatial-probability distributions of hydraulic parameters to describe variability in hydraulic habitats. Methods for predicting distributions of the two ecologically relevant hydraulic parameters of depth and velocity are described in the sections that follow.

7.2.3.1 Predicting Probability-Depth Distributions

Statistical analyses of the frequency-occurrence of flow depth along surveyed cross-sections provide measurement-based data on their spatial distribution.

For a specified maximum depth (and related discharge as determined from rating data – eg. Fig. 7.2 and Table 7.1), the actual depths along a cross-section are computed at equal distance increments. This is preferable to using actual surveyed elevations across the river bed, since these are usually measured at changes in slope and with a higher density of bed elevations in the low-flow channel (ie. not valid data for a statistical analysis). The range of depths (zero to maximum) along a cross-section/s are divided into equal depth class increments, and the frequency of occurrence within each depth class are computed. Figure 7.8 provides example plots of the frequency-depth distributions along cross-sections through a rapid and pool at a site on the Little Thukela River (KZN).

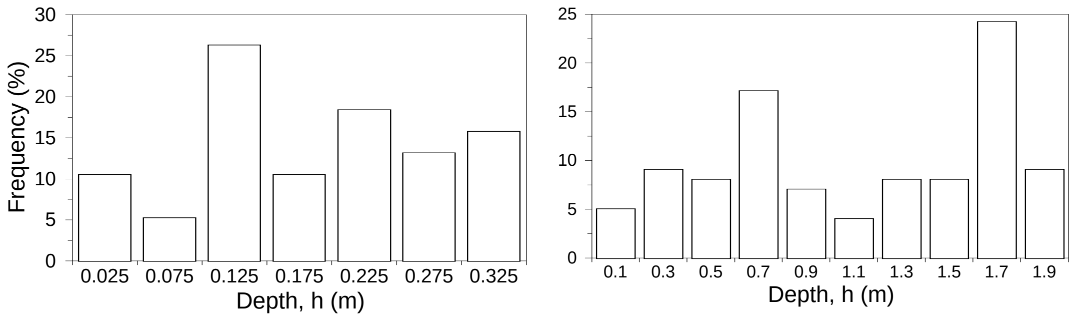

Figure 7.8 Example plots of frequency-depth distributions along cross-sections through rapid (left) and pool (right) morphologies, for a discharge of 0.46m^3/s (Average and maximum depths in the rapid are 0.18m and 0.35m, and in the pool are 1.11m and 1.82m, respectively)

The frequency-depth distributions in Fig. 7.8 are computed from single surveyed cross-sections profiles through rapid and pool morphologies. To describe typical variability in the distributions, surveys need to provide representative cross-sectional profiles through the different morphological features. Depth probability distributions for river reaches were modelled by Lamouroux (1998).

Depth-probability distributions in stream reaches (Lamouroux, 1998)

The analysis is based on two data sets: the first included 104 distributions measured at various discharges in 22 different reaches in the Ruhr (Germany) and Bavarian River catchments; the second included 47 distributions measured for a range of discharges in 8 reaches of the Rhône and Ain Rivers in France. The reaches contained several pool-riffle sequences.

In all reaches, distributions of the relative depth (*h*/*H*) changed with increasing stage from exponentially shaped distributions, indicating a high variability of depth values, to normally shaped distributions, where values concentrated around the mean. This trend was modelled using a parametric density function that is a combination of two extreme models: exponential and normal distributions, and is expressed as

$$f\left(x=\frac{h}{H},t\right)=te^{-x}+0.951(1-t)e^{-\left(\frac{x-1}{0.593}\right)^{2}} \qquad 7.2$$

in which h is depth (m), H is the mean reach depth (m) and t is a shape parameter varying from 0 (normal distribution) to 1 (exponential distribution).

Equation 7.2 reduces determining the depth-probability distribution to the evaluation of the shape parameter t. Unlike for velocity-probability distributions, Lamouroux (1998) could not correlate t with hydraulic indices such as the relative roughness or Froude number (refer to section 7.2.3.2). However, a reduction in the shape parameter value is associated with the evolution of depth distributions from exponential to normal with increasing stage. Based on this, the change in the shape parameter (Δt) was found to be best correlated with Δ ln(H), given by

$$\Delta t=-0.7\,\Delta\, ln(H) \qquad 7.3$$

Application of this model for predicting depth distributions in a reach as a function of discharge requires an estimate of the depth distribution (or shape) parameter at a given stage, and a knowledge of the mean depth-discharge (rating) relationship for the reach. Two drawbacks of the model are the need to measure flow depths to provide an estimate of the shape parameter, and applicability for river reaches containing different morphological features (ie. pool-riffle sequences). Disaggregated distributions for different features are preferable, since different biota show preferences for hydraulic habitat associated with different morphologies.

7.2.3.2 Predicting Probability-Velocity Distributions

River biota (particularly fish and macroinvertebrates) also display preferences for hydraulic habitats containing certain ranges of velocity. Ecologically relevant and reliable velocity data is difficult to provide for natural rivers containing large relative roughness, and the limitations of two and three-dimensional hydraulic modelling are discussed by Lamouroux *et al* (1995). The modelling of characteristic frequency-velocity relationships is therefore valuable for providing typical spatial distributions.

Probability distribution of velocity in natural channel cross-sections (Dingman, 1989)

Dingman (1989) proposed a power law for the cumulative distribution of point velocity in a cross-section based on a theoretical and statistical analysis of logarithmic and power law velocity distributions, given by

$$F(v) = \left(\frac{v}{U}\right)^{c} \qquad 7.4$$

in which v is the local or point velocity (m/s), U is the maximum cross-sectional velocity (m/s), and c is a shape parameter.

Although measured cross-sectional velocities confirmed the form of equation 7.4 for idealised, regular and irregular natural channels, the distribution parameters (maximum velocity and shape) could not be related to any measurable parameters, limiting its application. Lamouroux *et al* (1995) developed a useful predictive model with distribution parameters that are related to descriptors of hydraulic variables in river reaches.

Predicting velocity distributions in stream reaches (Lamouroux et al, 1995)

The data used for model development were collected from 37 river reaches in France, with reach lengths ranging from 2 to 20 times the flow widths. Reaches were divided into between 3 and 17 longitudinal divisions, with each division further divided into transverse cells (from about 100 to several hundred cells). Depth averaged velocities were determined from point measurements at 20, 40 and 80% of the flow depth, measured from the bed. Point measurements were often found to deviate from theoretical logarithmic profiles (developed based on boundary shear at the bed), since both emergent and submerged conditions were considered. The average dominant bed roughness was used, defined by the size of the roughness elements occupying the largest fraction of the bed. To allow valid statistical analyses, depth and roughness measurements were weighted using cell area (bed), and depth-averaged velocity was weighted using cell volume.

The measured frequency-velocity distributions varied from centred distributions with velocities grouped around average reach values, to decentred distributions with bi-modal velocity distributions. A probability density function was defined using a combination of a Gaussian distribution (centred), and Gaussian and exponential distributions (decentred), given by:

$$f\left(x=\frac{v}{V},s\right)=s\left(3.33e^{-\frac{x}{0.193}}+0.117e^{-\left(\frac{x-2.44}{1.73}\right)^2}\right)+(1-s)\left(0.653e^{-\left(\frac{x-1}{0.864}\right)^2}\right) \qquad 7.5$$

in which v is the depth averaged velocity (m/s), V is the average reach velocity (m/s) and s is the shape parameter.

The shape parameter was correlated with five dimensionless variables, and three relationships were developed with combinations of three variables (the Froude number, relative roughness and the width variability). The function (equation 7.6) based on Froude number (Fr) and relative roughness (D/H) yielded a regression coefficient, R^2 = 0.75. The width variability added little additional explanation to the prediction of the shape parameter (R^2=0.78).

$$s = -0.275 - 0.237(\pm 0.057)\ln(Fr) + 0.274(\pm 0.361)\frac{D}{H} \qquad 7.6$$

in which *H* is the mean reach depth (m).

Examples of predicted probability-velocity distributions for a site on the Elands River (Incomati River System) at the foot of the Drakensberg escarpment (Fig. 7.9) are plotted in Fig. 7.10 for discharges of 0.78m^3/s and 9.7m^3/s. The hydraulic parameter values (with the addition of the maximum velocity) used in the probability density (equation 7.5) and shape functions (equation 7.6), are given in Table 7.8. These data are derived from hydraulic analyses using a surveyed cross-sectional profile through the rapid, and measured rating data. The influence on the distributions of reducing the mean roughness value (from 0.3m to 0.1m) is also indicated in the plots (Fig 7.10).

Table 7.8 Parameter values used in probability-velocity analysis

Hydraulic variable	Discharge, *Q* (m^3/s)			
	0.78		9.7	
Mean depth, *H* (m)	0.30	0.30	0.60	0.60
Maximum depth (m)	0.65	0.65	1.09	1.09
Mean velocity, *V* (m/s)	0.15	0.15	0.70	0.70
Mean roughness, *D* (m)	0.30	0.10	0.30	0.10

Figure 7.9 View of the Elands River site for a discharge of 0.78m^3/s, showing the large roughness elements (Photo A Birkhead)

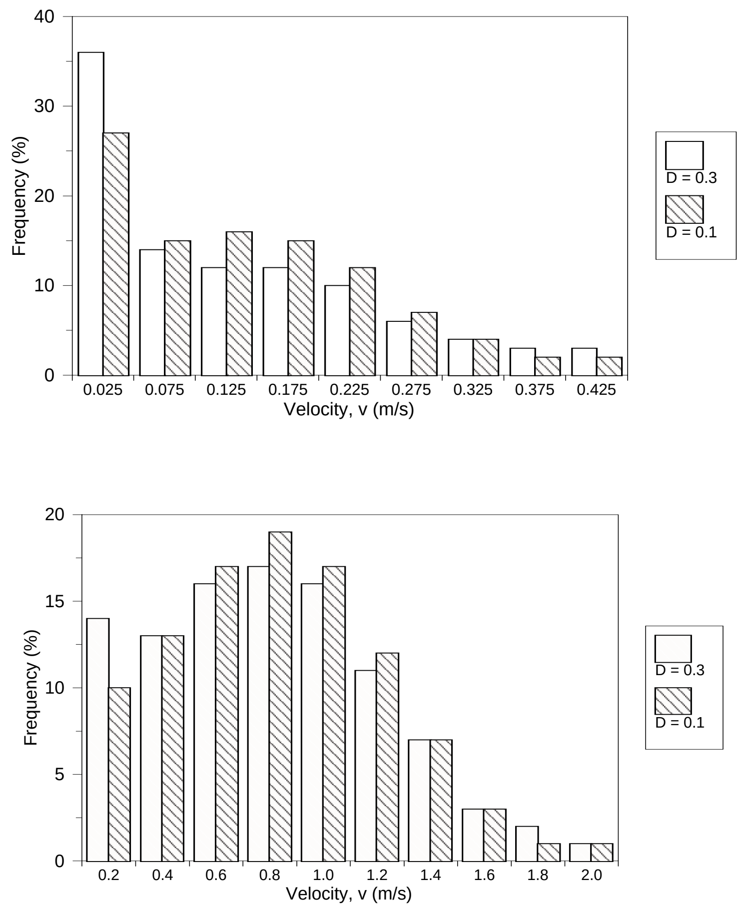

Figure 7.10 Examples of modelled probability-velocity distributions according to Lamouroux *et al* (1995) for discharges of 0.78m^3/s (top) (refer to Fig. 7.9) and 9.7m^3/s (bottom) at the Elands River site. The legend denotes mean roughness value (*D*)

The data used in the analysis included measurements from one to several pool-riffle sequences. Lamouroux *et al* (1995) mentions the need to undertake further studies investigating velocity distributions within homogenous geomorphological units (eg. rapids, riffles and pools). As discussed in Section 7.2.3.1 with reference to the reach based depth-probability distribution of Lamouroux (1998), disaggregated functions for different features are desirable, because different biota display preferences for hydraulic habitat associated with different morphologies. Jonker *et al* (2002) adopted a similar approach to Lamouroux *et al*. (1995) to predict the velocity distributions in cobble and boulder bed river in the Western Cape for three dominant types of morphological features, including rapids and riffles, plane beds and pools.

Probability distribution of local velocities in cobble and boulder bed rivers (Jonker et al, 2002)

Randomly measured point velocities (depth-averaged) were used to define relative velocity (*v*/*V*) distributions for the three morphological units. Unfortunately, limited data sets were used in the analyses (9, 10 and 12 sets of distributions for the plane bed, pool and rapid/riffle morphologies, respectively). The following probability distributions were fitted to the data: Normal and Log-normal, Extreme type I, Gamma, Rayleigh and Weibull. The goodness-of-fit was evaluated both visually, and using Chi-square and Kolmogorov-Smirnov tests. From this, it was concluded that the morphologies considered are best represented by the following distributions: Rapid/riffle – Extreme followed by Weibull; pool – Weibull; plane bed – Extreme and Weibull.

The Extreme Type-I and Weibull distributions are given by equations 7.7 and 7.8, respectively.

$$f(x = \frac{v}{V}, \alpha, \beta) = \alpha e^{-\alpha(x-\beta)-e^{-\alpha(x-\beta)}} \quad 7.7$$

in which α is a scale parameter and β is a location parameter.

$$f\,(\,x=\frac{v}{V}\,,\alpha,\beta\,)=\alpha\beta x^{\beta-1}e^{-\alpha x^{\beta}} \qquad 7.8$$

in which α is a scale parameter and β is a shape parameter.

The parameters (α and β) used to calibrate these distributions were correlated using multiple linear regression with the following hydraulic indices: Froude and Reynolds numbers, velocity/depth ratio, relative submergence and the width/depth ratio. The results are provided below for the rapid/riffle and pool morphologies. For the plane bed morphologies, there were no statistically significant correlations between the distribution parameters and the hydraulic indices tested.

Rapids and riffles

For the Extreme distribution (equation 7.7), the scale and location parameters are given by

$$\alpha = 1.000(\pm 0.205) - 0.442(\pm 0.253)\frac{H}{d_{50}}$$
$$\beta = 1.167(\pm 0.169) - 0.360(\pm 0.207)\frac{H}{d_{50}} \qquad 7.9$$

with regression coefficients (R^2) of 0.57 for both correlations. The 95% confidence limits are provided in parentheses.

For the Weibull distribution (equation 7.8), the correlation for the shape parameter (β) gave a low regression coefficient of 0.34, and is therefore not provided here.

Pools

For the Weibull distribution (equation 7.8), the scale and shape parameters are given by:

$$\alpha = 1.877(\pm 0.162) - 0.299(\pm 0.078)Re$$

$$\beta = 1.556(\pm 0.732) + 241.262(\pm 191.18)Fr - 28.540(\pm 23.950)\frac{V}{H} - 1.351(\pm 1.143)Re \quad 7.10$$

with regression coefficients (R^2) of 0.94 and 0.77, respectively. The shape function (β) is not statistically significant at the 5% level.

Prediction of velocity distributions for rapids and riffles differ from those of Lamouroux *et al* (1995). This may be partly attributed to the latter models being applicable to distributions in river reaches containing riffles and pools, and therefore a higher frequency of occurrence of low-velocity classes (from the pools) is expected. The accuracy of the predictions by Jonker *et al.* (2002) has not been established, since the models have not been verified using distribution parameters (α and β) determined from independant field data (not used in their calibration, ie. equations 7.9 and 7.10). This is necessary, given the low regression coefficients (R^2=0.57) of the correlations. Furthermore, the range of applicability, expressed in terms of certain hydraulic parameters and indices (Froude and Reynolds numbers, velocity/depth ratio and relative submergence) need to be defined.

Therefore, of the available velocity distribution models in the literature, the model of Lamouroux *et al* (1995) appears to be the most robust and tested. A drawback, however, is that the model has been developed for pool-riffle sequences and not homogeneous geomorphological features.

7.2.3.3 Scoring the Relative Abundance of Hydraulic Habitat Type

Cross-sections at river sites and their associated rating functions are required to characterise the local morphology and stage-discharge behaviour (Rowlston *et al*, 2000 and Birkhead, 2002). Therefore, the standard hydraulic information synthesized for a cross-section (eg. Table 7.1) represents average values for the local morphological feature (eg. rapid, riffle, pool, etc.), and can be used to estimate typical velocity distributions (eg. Lamouroux *et al*, 1995). The shape factor (equation 7.6) also requires an estimate of the dominant bed roughness, defined as the roughness element occupying the largest fraction of the bed. Although this would require a visual estimate for rapid ecological flow assessments, more comprehensive assessments include a survey of the bed material for sediment transport analysis. If measured sediment size distributions are available, the size occupying the largest fraction of the bed is more accurately determined from the product of the projected sediment area and its frequency of occurrence. Depth distributions are provided directly, using the cross-sectional profile/s (eg. Fig. 7.1). Using these distributions, the percentage of depth and velocity values falling within certain classes may be assessed for different flows. The overall abundance (expressed as a percentage) of different hydraulic habitat types (ie. velocity-depth classes) can then be determined by assuming that velocity and depth are mutually exclusive hydraulic variables (Table 7.10a). Under these conditions the hydraulic habitat falling within any habitat type is calculated by the product of the percentage abundance of the velocity and depth within the class. For riffle and rapid type features at certain sites, however, depth and velocity may be mutually dependant variables, particularly the SS and FD categories (ie. shallow flow will be slow, and deep flow will be fast). Under these conditions, the abundance (percentage) of a certain class is given by the lower of either the depth or velocity requirement defining the hydraulic habitat type (eg. Table 7.10c for SS and FD hydraulic habitat types).

The abundance of hydraulic habitat type is converted from percentage occurrence to relative numeric values (or scores) in the range 0 to 5 using, for example, the classification proposed in Table 7.2. A “moderate” rating (score of 3) accounts for a large proportion of mid-range values (25%-75%), thereby limiting the sensitivity of the scoring system. For this reason, the descriptors, relative scores and percentage occurrences may require refinement (eg. Table 7.9).

Table 7.9 Abundance scoring for hydraulic habitat types for fish

Descriptor	Score	Occurrence (%)
None	0	0
Rare	1	0-10
Sparse	2	10-30
Moderate	3	30-60
Abundant	4	60-80
Very abundant	5	80-100

In *Step 1* of the method for assessing the ecological flows for fish using habitat types (refer to Section 7.2.2.1.2), the abundance of the four velocity-depth classes are rated (visually and by taking velocity and depth measurements) during on-site investigations. It is therefore necessary to reconcile the on-site abundance assessments (*Step 1*) with values determined from the hydraulic modelling (ie. Tables 7.10b and 7.10c). Reasons for differences include: the influence of substrate and cover features which are not considered in the assessment of hydraulic habitat type abundance (ie. Tables in 7.10), the subjectivity inherent with on-site assessments, the use of cross-sectional specific data to represent characteristic hydraulic habitat, the use of a reach-based velocity distribution model (refer to Section 7.2.3.2), and the absolute size of the river. Agreement in the abundance scorings derived from the semi-quantitative modelling approach (described in this section) and on-site evaluations (*Step 1*) should be achieved by taking account of the above considerations. Measured flows (shaded rows in the Tables of 7.10) are generally accompanied by site photographs. These provide additional visual information to verify the modelled predictions as well as the extent and suitability of cover (refer to Section 7.2.2.1). The hydraulic modelling approach forms the basis for extending the discharge range for which abundance scores are required.

Standard hydraulic analyses (eg. Table 7.1) provide the average cross-sectional velocity. Experience with measuring velocities in riffle and rapid morphological units has indicated that the maximum value is usually 2 to 3 times the average value, and this information has been used by ecologists during flow assessments. The velocity distribution model of Lamouroux *et al* (1995) supports this field-based experience, with maximum estimates approximately three times the average values (eg. Fig. 7.11 and Table 7.10a), and approximately 10% of the velocities are greater than twice the average values.

The extent and suitability of cover is assessed on-site during *step 1* of the procedure (refer to Section 7.2.2.1). A topographical survey of marginal vegetation (rooting depth and crown elevation), analysed in conjunction with inundation and stage level information, augments on-site assessments and photographic evidence. Unless a three-dimensional spatial model for the site is being developed, the position of marginal vegetation is related to cross-sectional profiles.

Although this section has dealt almost exclusively with the scoring of hydraulic habitat type abundances for fish, the procedure is also applicable to macroinvertebrates (refer to Section 7.2.2.2).

An approach for the evaluation of fish habitat quality and instream flow assessment using fuzzy-rule based models (Schneider and Jorde, 2003), shows higher correlation with actual fish findings than the use of preference functions (eg. used in PHABSIM). This rule-based approach is part of the CASiMiR (Computer Aided Simulation Model for Instream Flow Requirements) simulation model, developed from the early 1990's. There is a similarity between the "fuzzy-rules" and the habitat-type categories described for fish (and macroinvetebrates). This modelling approach shows promise, and deserves further investigation.

Three-dimensional spatial modelling of physical and hydraulic habitat is discussed in the Section 7.3, and provides additional information on the extent of inundation and connectivity between areas of varying depth.

Table 7.10a Tabulated hydraulic parameters and percentage of hydraulic habitat meeting defined types, assuming that depth and velocity are mutually exclusive variables

Discharge (m^3/s)	Depth, *H* (m)						Velocity, *v* (m/s)				Habitat type (%)				Width (m)
											SS	SD	FS	FD	
											V<0.3	V<0.3	V>0.3	V>0.3	
	Max.	Ave.	%<0.5	%>0.5	%<0.3	%>0.3	Ave	Max	%<0.3	%>0.3	H<0.5	H>0.5	H<0.3	H>0.3	
0.12	0.44	0.16	100	0	90	10	0.06	0.15	100	0	100	0	0	0	14.4
0.38	0.56	0.24	94	6	65	35	0.10	0.25	100	0	94	6	0	0	17.8
0.78	0.65	0.30	91	9	52	48	0.15	0.40	94	6	86	8	3	3	19.3
3.0	0.77	0.44	68	32	22	78	0.35	1.0	55	45	37	18	10	35	13.6
4.0	0.83	0.48	64	36	23	77	0.41	1.2	50	50	32	18	12	39	24.0
9.7	1.09	0.60	31	69	26	74	0.70	2.0	25	75	8	17	20	56	26.8
15.0	1.24	0.67	35	65	19	81	0.88	2.6	17	83	6	11	16	67	30.2

Table 7.10b Abundance scorings (mutually exclusive)

Discharge (m^3/s)	Abundance scoring			
	SS	SD	FS	FD
	V<0.3	V<0.3	V>0.3	V>0.3
	H<0.5	H>0.5	H<0.3	H>0.3
0.12	5	0	0	0
0.38	5	1	0	0
0.78	5	1	1	1
3.0	3	2	1	3
4.0	3	2	2	3
9.7	1	2	2	3
15.0	1	2	2	4

Table 7.10c Abundance scorings (mutually dependant)

Discharge (m^3/s)	Habitat type (%)		Abundance scoring	
	SS	FD	SS	FD
	V<0.3	V>0.3	V<0.3	V>0.3
	H<0.5	H>0.3	H<0.5	H>0.3
0.12	100	0	5	0
0.38	94	0	5	0
0.78	91	6	5	1
3.0	55	45	3	3
4.0	50	50	3	3
9.7	25	74	2	4
15.0	17	81	2	5

7.3 Three-Dimensional Spatial Modelling of Physical and Hydraulic Habitat

7.3.1 Background

As with most methods used in environmental flow methodologies, confidence in recommended flows depends on the detail of hydrological, hydraulic, geomorphological and biological information available. In South Africa, EFRs have relied on hydraulic information derived for two-dimensional cross-sections (generally one per river site), and single stage-discharge relationships (refer to Section 7.2.2). Confidence is improved if assessments of the physical and hydraulic habitat components can be based on a broader spatial characterisation of site conditions. This is being addressed in Reserve studies by integrating hydraulic analysis with three-dimensional (3d) spatial models, as well as substrate-type and vegetation mapping. This is termed "3d spatial modelling", and should not be confused with 3d hydraulic modelling. Hardy (1998) provided a review of methods and procedures for characterising the components of "habitat modelling", these being spatial, hydrodynamic and biological elements. He maintains that habitat modelling remains an abstraction, since integration of all these components has yet to be accomplished. For this reason, the term "habitat modelling" is inappropriate for describing its existing application in Reserve studies.

Waddle *et al* (1997) employed two-dimensional (2d) hydraulic (CDG2D model) and habitat modelling of the Yellowstone and Upper Missouri Rivers in an attempt to assess habitat requirements of the Great Plains fish communities. Their use of 2d modelling is an attempt to overcome difficulties associated with the traditional one-dimensional approaches (eg PHABSIM, Milhous *et al*, 1989), which avoid important habitat areas in complex channels. More recent versions of PHABSIM (Physical Habitat Simulation System) include 2d hydraulic modelling.

Three-dimensional spatial models of river sites for Reserve studies concentrate primarily on the characterisation of the spatial and hydraulic domains, with the objective of providing more accurate physical and hydraulic templates (than may be achieved using cross-sections and single rating relationships). Resources available for topographical surveys dictate that only a portion of a river site is mapped. This implies that steady-state hydraulic analyses are appropriate, rather than hydrodynamic modelling. The integration of biological aspects is included separately in the flow assessment procedure, using, for example, the habitat descriptions for fish and macroinvertebrates provided in Section 7.2. Surveys are also used to indicate the position of vegetation on an overlay of the physical template. Three-dimensional spatial models are useful for characterising river sites that contain a diversity of hydraulic and physical habitats that cannot be adequately described using single transects.

Three-dimensional spatial models developed for the Olifants and Thukela River Reserves (DWAF, 2001; 2004) used a Geographical Information System (GIS). ArcView, together with a spatial analyst were used to manipulate spatial point (raster) data to create a model of the bed topography and distribution of sediment sizes (Fig. 7.11b). The elevation data were surveyed using a series of transects across the river. A filled elevation contour is used to display the inundated area corresponding to a given discharge, and implies a horizontal water surface. In Reserve studies, 3D spatial models are usually prepared for rapid and riffle features (eg. Fig. 7.9), that are characterised by non-uniform flow conditions (i.e. that change with distance along the river) and appreciable water surface slopes. The use of contours to graphically depict inundated areas requires a single stage level in the mapped region, and this is achieved by adjusting the elevation of the bed topography (at each survey point) by an amount that maintains the correct flow depth. The elevation of the bed topography is generally adjusted for flow conditions at the time of survey. The bed elevation adjustment to allow for the use of contours implies that stages change by equal increments as a function of discharge within the entire mapped area, and may result in inaccurate modelled water surface elevations (and hence inundated areas) at flows different from that at the time of survey. From a hydraulics perspective, this is a major drawback, and more rigorous modelling techniques have therefore been investigated in this project. The GIS platform and associated software provides useful tools, however, for analysing inundation and substrate information. For example, it may be used to compute the combined spatial distributions of depth and sediment size as a function of discharge.

Wadeson and Rowntree (in prep) describe a research project assigned with the objective of developing a geomorphological method for describing discharge related changes in instream hydraulic habitat using hydraulic biotope mapping, and applying this to assist ecological Reserve determinations. These objectives of their project have commonality with the study described in this report, and a review and discussion of their approach is therefore provided:

The limitations of standard hydraulic analyses in Reserve determinations that employ single cross-sectional river profiles (as described in detail in this chapter) are used as a premise for developing a method that assesses spatial changes in hydraulic habitat across “whole” geomorphological units (rapids and riffles - being the focus of Reserve assessments). The ability of two-dimensional [hydraulic] modelling to provide distributions of depth and velocity is recognised, as are difficulties with its application in environments with large relative roughness elements (discussed further in Section 7.3.2 following), and data requirements.

The authors suggest the use of hydraulic biotope mapping, involving the visual classification of hydraulic characteristics as discerned from the “flow-type” viewed at the water surface. Flow-types include, for example, barely perceptible; smooth water surface; rippled and surging flows. Hydraulic biotopes are a classification of hydraulic habitat based primarily on flow-type, and include, for example, pools, glides, runs, riffles, rapids and chutes. The authors mention the time-consuming nature of biotope mapping, and the need to develop practical methods for use in Reserve studies. There is no further mention of such methods, however, and the study employed re-mapping at different discharges using tape measures for re-positioning. Four sites were used in the study: two sites in the Sabie River (Mpumalanga Province) and two in the Kat River (Eastern Cape). All the sites are characterised by large roughness elements, typical of Reserve sites.

The data collection used in the study of Wadeson and Rownstree (in prep) involved: the survey (using transects) of the bed topography, sediment type and vegetation as undertaken in Reserve studies (ie. Fig 7.11b), but with the addition of biotope classification; the re-mapping of hydraulic biotopes at three different discharges for three of the sites; the measurement of discharge; and the recording of stage from local stage-plates. GIS software was used to prepare the coverages, as discussed previously (Fig.7.11b), with additional coverages of the spatial distribution of hydraulic biotopes (one for each observed flow). Spatial distributions of depth were also determined for each of the measured discharges. To do this, bed elevations were adjusted (not “corrected” as stated in their report) relative to water elevations – since in the GIS analysis, contours are used to represent stage, and therefore only one stage level is possible across the entire mapped region for a given discharge. Inaccuracies associated with this were discussed previously. Analyses were also carried out to compute the frequency distributions of biotopes as a function of depth, for each of the observed flows.

The mapping of hydraulic biotopes provides useful information on the spatial distribution of different hydraulic habitats (visually), and their frequency distributions. Problems with this approach are that this semi-quantitative information is related to only observed discharges; data collection for a range of flows is time-consuming; it is difficult to interpolate and extrapolate observed trends at a site; and the results are site-specific due to the usually unique and complex hydraulic characteristics of Reserve sites. Their discussion notes that the spatial and frequency distribution of biotopes between sites are very different. More fundamental quantitative studies of hydraulic habitat and changes with discharge are therefore required.

Figure 7.11a View of a Reserve site on the Buffalo River in Kwazulu-Natal. Flow direction is from left to right. (Photo D. Louw)

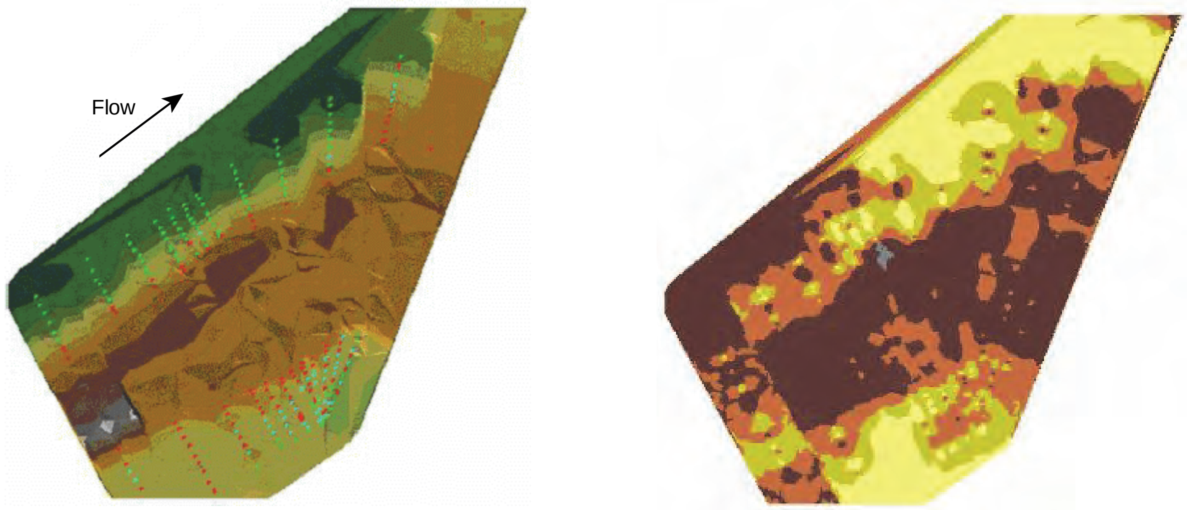

Figure 7.11b (left) Digital terrain model of the Buffalo River Reserve site shown in Fig. 7.11a. The length of channel mapped is approximately 140m (measured along the thalweg), and the positions of transects are indicated by the overlay of vegetation types (coloured markers) at the channel margins (shading: from white (0 m) to dark brown (1.2 m) to dark green (4.7m)). (right) GIS coverage of the spatial distribution of sediment type (shading: yellow(silt) to light brown(cobble) to dark brown(boulder) to grey(bedrock)) (DWAF, 2004)

Wadeson and Rowntree (in prep) include a discussion on the application of biotope mapping to ecological flow assessment. A few statements deserve further clarification:

Depth mapping for a range of flows requires either hydraulic modelling, or periodic water surface surveys and measurement of discharge. The method whereby bed elevation contours are used to denote depth contours requires an adjustment of the bed topography for each survey point relative to the water elevation, as discussed previously. This is coupled with the hydraulic (modelling) assumption that stages change by equal increments across the entire inundated area with changes in discharge. This allows subsequent stage levels to be recorded at only one location within the mapped area. With no further hydraulic modelling, depth distributions are available for only <u>observed</u> stages, which limits application of the method in Reserve determinations.

Hydraulic biotopes have been related to the hydraulic index known as the Froude number (Wadeson and Rowntree, 2001), which is a function of depth and velocity. The authors propose that a combination of depth and biotope mapping be used for inferring flow velocity. The accuracy of this approach is questionable. Firstly, there is a high variance in Froude number, even for homogenously classified biotopes such as riffles, rapids and chutes (that are characterised by rapidly varied flow), and flow conditions usually include both supercritical and subcritical. Secondly, the inaccuracy of using a single stage contour to represent the water surface elevation for the entire mapped region has been discussed. Taking account of these uncertainties, there is a cumulative inaccuracy of determining velocities using this approach. Furthermore, biotopes require on-site mapping, during which time velocities may in any case be measured directly.

The value of the modelling approach using GIS (eg. Fig. 7.11b) has already been established in Reserve studies, and provides a visual display of the connectivity between areas of different depth. Biotope mapping (as described by Wadeson and Rownstree, in prep) provides additional information for use in 3d spatial modelling, and should not be confused with hydraulic modelling, which is an integral and key component of habitat modelling (Hardy, 1998). The unsatisfactory application of hydraulic analysis in 3d spatial modelling for Reserve studies has resulted in alternative approaches being investigated.

7.3.2 Modelling Approach

One-dimensional (1d) steady-state hydraulic modelling is being used in combination with Digital Terrain Modelling (DTM) to provide 3d spatial models of river Reserve sites, and are generally used at the Comprehensive level of determination which require high confidence assessments. A drawback of 1d hydraulic modelling is that average velocities are computed for cross-sections that assume horizontal water surface profiles (across the channel). Typical frequency distributions of velocity (depth averaged) can be predicted using, for example, the probability models described previously in Section 7.2.3.2. With careful positioning of cross-sections, orthogonal to the flow direction (eg. Fig 7.11), horizontal cross-channel stages may be assumed. 3d spatial models provide valuable information for flow assessments at sites characterised by complex morphologies and associated diversity of hydraulic habitat types. These characteristics suggest, however, that two-dimensional hydraulic modelling is appropriate.

Surfacewater Modelling System (SMS) is marketed by Boss International (web site www.bossintl.com) as the most advanced two-dimensional dynamic flow software available.

SMS is organised into six modules, five of these are of relevance to 2d hydraulic modelling: the map, mesh, scatter point, RMA (Resource Management Association) and HIVEL interface modules. Using the map module, digitised images can be displayed and used for onscreen digitising and background images. Images can be registered (geo-referenced) so that pixels correspond with real world survey coordinates. A background image provides a frame of reference for developing the surface water model. The mesh module provides automated tools for constructing finite element meshes covering a region of any arbitrary shape. The scatter point module provides two-dimensional interpolation tools for interpolating scattered point data to a finite element mesh. The RMA interface module provides a graphical interface to the US Army Corps of Engineers RMA-2 analysis engine. RMA-2 is a two-dimensional depth averaged free surface finite element model for subcritical flow conditions, whereas HIVEL-2D is for flow fields containing both supercritical and subcritical flow regimes. Panfil and Jacobson (1999) used SMS to model hydraulic conditions at a site in the Ozark Highlands of the Missouri River as part of a study of physical habitat sensitivity to climate change. A GIS was used to process and further analyse modelled hydraulic data.

In Reserve studies considerable attention is focussed on the low-flow component of the hydrological regime, and sites are often characterised by large-scale roughness (eg. Fig. 7.9). This requires the analysis of shallow flows with complex boundaries (due to emergent bars and substrate elements), which produces numerical instabilities. Complex flow boundaries are illustrated in Fig. 7.14, which shows the inundated area at the site in Fig. 7.13 for a flow of 0.36 m^3/s. Accurate modelling would require detailed topographic (including substrate) surveys and the use of a dense mesh, since flow through a number of adjacent nodes is required for stable numerical solutions. Furthermore, meshes may need to be re-constructed for different flows, due to changes in the position of boundaries and orientation of streamlines with changes in discharge (eg. Panfil and Jacobson, 1999). Kondolf *et al* (2000) maintains that highly accurate hydraulic modelling may be infeasible for rivers with complex channel geometry, and furthermore cannot resolve flow patterns at spatial scales at which fish often respond to the hydraulic environment. For these reasons, 1d hydraulic modelling has been favoured for use in Reserve studies for sites with large roughness elements, and a suite of three modelling tools have been used for this purpose:

- QuickSurf
- RiverCAD

- HEC-RAS

This software was also used in the hydraulic study of the Nyl River Floodplain, described by Birkhead *et al* (2004).

7.3.2.1 Digital Terrain Modelling

Quicksurf is a general purpose surface modelling system running inside of FelixCAD. Quicksurf converts surface mapping data such as point and/or break-line data into contours, grids (GRDs), triangulated irregular networks (TINs), and triangulated grids (TGRDs). A suite of tools allows the manipulation of surfaces into high quality maps. Quicksurf version 5.1 and FelixCAD version 2.1 were used in this project.

Digital contour maps of the river bed topography are prepared using Quicksurf, which operates under the FelixCAD platform. Quicksurf uses surface memory storage, rather than a drawing database, to reduce the amount of memory required to manipulate data thereby providing fast execution of modelling operations. A surface is stored in CAD-controlled memory and only becomes part of the drawing when it is added ("show "or "draw" operations) to a layer. Entities drawn to a layer can only be manipulated using Quicksurf functions after they have been "extracted" to a surface. Surfaces are saved as "qsf" extensions from QuickSurf, independent of the FelixCAD drawing, which is saved with a "flx" extension.

Laser mapping is an emerging technology in the field of remote sensing that is capable of rapidly generating high-density, geo-referenced digital elevation data with an accuracy equivalent to traditional land surveys, but significantly faster than traditional airborne surveys. The technology allows for extremely rapid rates of topographic data collection, resulting in elevation point densities far greater than traditional ground survey methods. The reflectance of water is highly dependant on its surface state and usually has very little reflectance. For this reason, the laser does, unfortunately, not penetrate water. LIDAR (LIght Detection And Ranging) was successfully used to survey the Nylsvley Wetland, but required a pilot river channel, which was inundated at the time of the aerial survey, to be "cut" into the modelled surface. For this reason, the application of LIDAR for accurate mapping of river sites would require no surface water. The equipment used for mapping river sites includes the total station and differential Global Positioning System (GPS).

The method for preparing a digital site contour map is as follows:

- Point survey data is imported into the results or “dot” surface. This is a special surface maintained for loading data from an ASCII file, or for extracting data to a surface from CAD entities. The “dot” surface may subsequently be saved as a named surface. Figure 7.12 (left) is a plot of point elevation data for Reserve site on the Kei River in the Eastern Cape, shown in Fig. 7.13. Elevations were surveyed within 2.5 m wide swathes across the channel and at locations on the bed identified (visually) as being “changes in gradient”. This provides a more accurate elevation data set for DTM than the use of cross-sections, which rely on interpolation between transects (eg. Fig 7.11).
- Define a boundary using a two-dimensional polyline limiting the point data (and future operations, eg. gridding and contouring) to the floodplain area of interest, and save this in a boundary file for later use.
- Using the point data, generate a TIN, which is a three-dimensional model of a surface composed of planar triangulated faces. Generate an accurate contour map from the TIN and draw to a layer. Figure 7.11 (right) is an example of elevation contours at 5 cm elevation differences, generated from the point data in Fig. 7.11 (left) and associated TIN surface.

7.3.2.2 Positioning and Extracting Cross-Sections from the Digital Terrain Model

RiverCAD is an advanced graphical modelling environment, providing support for the US Army Corps of Engineers one-dimensional flow analysis software HEC-RAS (Hydrological Engineering Centre - River Analysis System). River cross-sections may readily be extracted from the digital contour map developed using QuickSurf. RiverCAD incorporates a facility for mapping inundation as well as a raster image module for loading geo-referenced digital images. Examples of 3d spatial modelling using RiverCAD 2000 are presented in this section. Future versions of RiverCAD will include a DTM to include surface modelling tools similar to those provided by QuickSurf.

RiverCAD provides the tools necessary for positioning and extracting cross-sections, measuring reach (channel and floodplain) distances between adjacent cross-sections, entering boundary conditions for steady-state hydraulic computations using HEC-RAS, and mapping flow inundation. Steady-state hydraulic computations can be performed within the RiverCAD modelling environment using the HECRAS version 2.0 module, whereas unsteady simulations require HEC-RAS version 3.0 or higher and HEC-RAS projects must be exported for this purpose.

- Firstly, the digital contour map prepared in QuickSurf is opened in RiverCAD. A digital orthophoto of the site may be loaded as a background image and geo-referenced by selecting the associated world coordinate file.
- Cross-sections are positioned and numbered from downstream to upstream within the mapped region. Cross-sections should be positioned (as far as possible given the often complex site morphology) orthogonal to the assumed flow direction, using regular intervals, and to account for abrupt changes in flow area due to the influences of hydraulic controls. Cross-sections may consist of a series of straight-line segments. Figure 7.14 shows the position of cross-sections (yellow transects) within the mapped area shown in Fig. 7.12.
- Once positioned, the cross-sectional profiles are generated automatically using contour data from user-defined layers (ie. the FelixCAD drawing layer containing the 10cm interval digital contour map in this case).
- "Flow lengths" define the length of the flow path between adjacent cross-sections, and may be specified separately for the channel, left and right banks. Left and right "bank stations" along the cross-sections allow different resistance coefficients to be used for the active channel and over-bank area – it may be necessary to use this facility to obtain satisfactory calibration of the water surface profile.
- The RiverCAD interface to the HEC-RAS steady-state flow analysis has been used for one-dimensional hydraulic modelling.

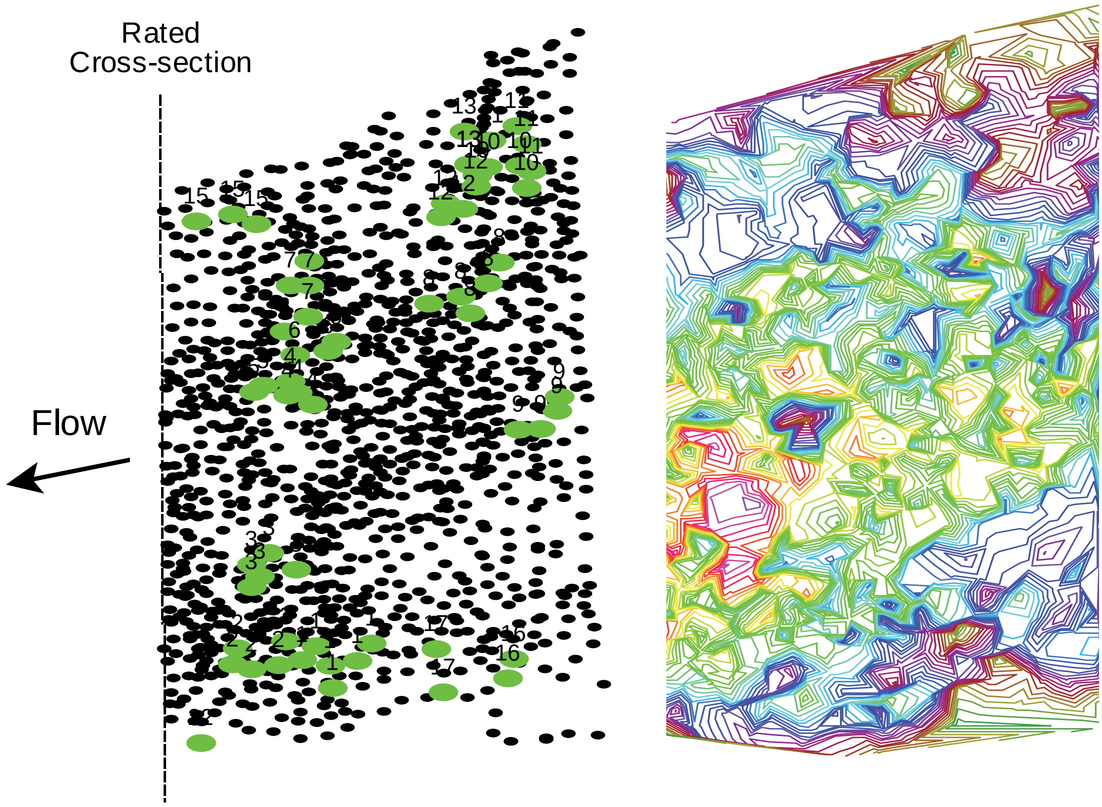

Figure 7.12 (left) Example of point survey data (black markers: bed, green markers: vegetation). The area covered by the mapping is approximately 11.5 m longitudinally by 20 m transversely. (right) Digital contour map with 5 cm contour intervals, prepared from the point survey data using QuickSurf

Figure 7.13 View of a Reserve site on the Kei River (Eastern Cape) facing down the rapid in the direction of flow for a discharge of 0.36 m^3/s (Photo D. Louw)

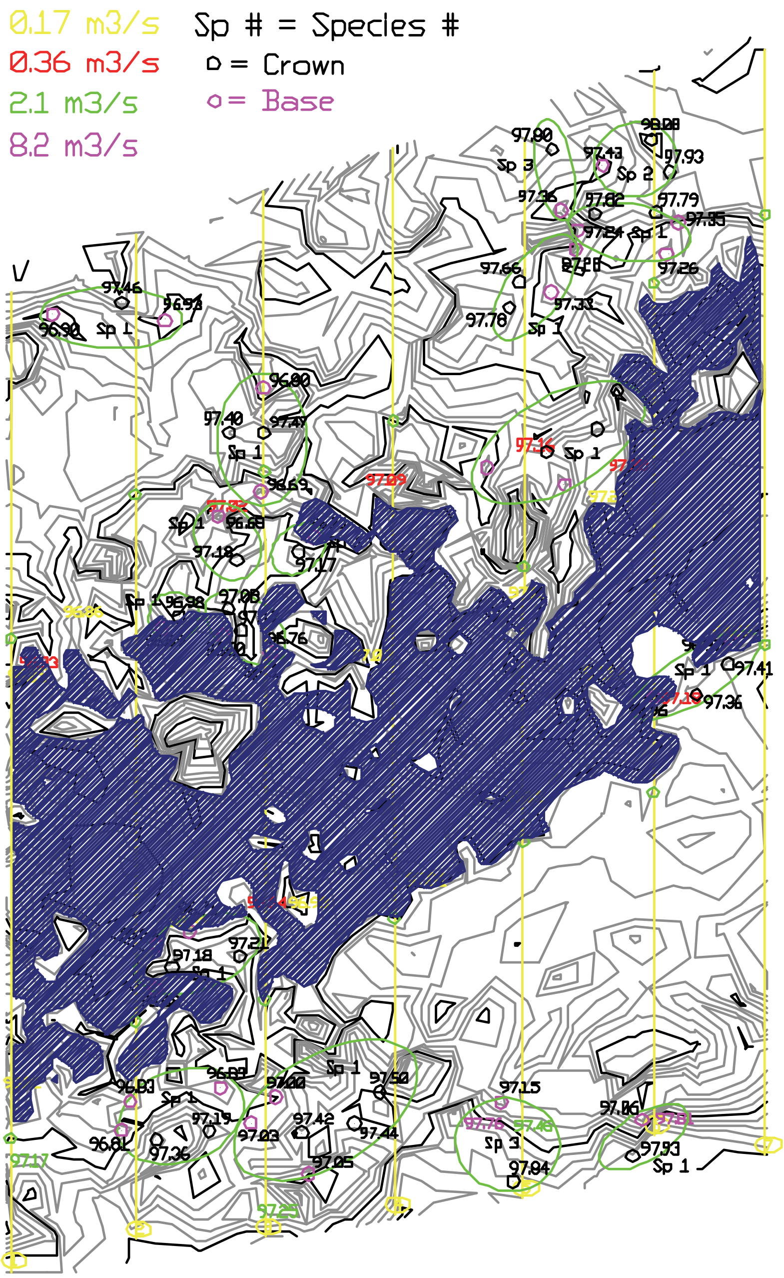

Figure 7.14 **3d spatial model for the Reserve site shown in Fig. 7.13, produced using RiverCAD. The contour interval is 10 cm and the flow direction is from right to left. The blue hatched region indicates inundation for a discharge of 0.36 m^3/s and the green ellipses demarcate clumps of vegetation**

7.3.2.3 One-Dimensional Hydraulic Modelling

HEC-RAS is a one-dimensional flow analysis software developed by the Hydrologic Engineering Centre of the US Army Corps of Engineers. It is part of the next generation

(NexGen) of hydrologic engineering software encompassing several aspects of hydrologic engineering, including rainfall-runoff analysis; river hydraulics; reservoir systems simulation; flood damage analysis; and real-time river forecasting for reservoir operation. HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking environment. The system comprises a graphical user interface, separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities. HEC-RAS software is free-domain, and may be downloaded with supporting manuals (Adobe PDF format) from the US Army Corps of Engineers HEC web site at www.hec.usace.army.mil.

HEC-RAS allows for the incorporation of levees and ineffective flow areas to exclude flow areas from the analysis, and flow resistance This allows modelled stages to better replicate measured values where a 1d analysis is used to simulate 2d conditions. Geometric data (cross-sectional profiles and reach lengths between them) form part of the RiverCAD analysis. Resistance coefficients (Manning's *n* is generally used), and the position of bank stations and ineffective flow areas, are adjusted as part of the flow calibration to achieve agreement between measured and modelled water surface profiles. HEC-RAS also provides the ability to specify flow-resistance factors that adjust flow resistance as a function of depth. This is a useful feature in vegetated and large roughness environments where resistance varies with stage (refer to James *et al*, 2001, and Birkhead 2000), but their use has been noted to produce solution instabilities.

For steady-state analyses, boundary conditions are required at either the downstream (eg. Fig 7.12), upstream or both boundary cross-sections, depending on whether flow is subcritical, supercritical or mixed, respectively. Boundary conditions take the form of measurement-based rating curves, derived from best-fit relationships between gauged discharge and observed stage levels (eg. Fig 7.2). As for the single cross-section and rating curve approach (discussed in Section 7.2.2), the hydraulic modelling of flows beyond the range of measured values relies on estimates of water surface gradient and flow resistance. Improved methods for the reliable prediction of these parameters for sites with large-scale roughness elements therefore remain a requirement. This is being investigated as part of ongoing environmental hydraulics research commissioned by the Water Research Commission (WRC Project no. K5/1405).

7.3.2.4 Displaying Inundated Areas Graphically

RiverCAD provides a facility to display the distribution of inundated areas, using the Floodplain Mapping Module. The data used for this is either from steady-state solutions analysed within RiverCAD, or profiles (solution at a particular time) which may be imported from an external unsteady flow analysis, eg. Birkhead *et al* (2004).

Figure 7.14 is a hatched rendering showing the modelled inundation for a discharge of 0.36 m^3/s at the river site shown in Fig. 7.13, and displays a complex spatial distribution due to uneven topography and large substrate. Realistically, the two small inundated areas that are isolated from the main channel should not be indicated as such, since they are separated from the channel flow. The mapping software allows the demarcation of flow with depths less than a specified value. This is useful for differentiating between "shallow" and "deep" flow using the Kleynhans (1999) habitat type classification for fish (refer to Section 7.2.2.1). Also, the flow depth at any grid position on the topographical map may be automatically determined. This is valuable for estimating the elevation of vegetation relative to the water surface.

7.3.2.5 Modelling the Submergence Depth of Vegetation

The co-ordinates of vegetation markers, representing indicators of vegetation structure that are useful for flow assessment, are included in the point data set (Fig. 7.12, left). These markers are indicated on the contour map and may include, for example, the elevation of the (base) bottom of the root wad and crown of clumps of marginal vegetation (eg. Fig. 7.14). The depth of submergence, measured from the bottom of the root wads, may then be determined as a function of discharge, using the depth tracking facility in RiverCAD.

7.3.2.6 Futher Developments

RiverCAD is an advanced graphical modelling environment, providing support for one-dimensional flow analysis software such as HEC-RAS, HEC-2 and DAMBRK. Results using alternative hydraulic analysis software may be graphically displayed through the data import facility (refer to Birkhead *et al*, 2004). GIS (Arcview and spatial analyst) may be used to visualise the spatial distribution of substrate, and analyse the combined distribution of substrate type and flow depth. A GIS interface module in RiverCAD allows for the definition and generation of GIS coverages using, for example, water surface elevation or flow depth contours and inundation fringe. These may be exported as ESRI shape files for further analysis using GIS. This development of 3d spatial modelling using GIS will enhance assessments of biological habitat (eg. Panfil and Jacobson, 1999).

Three-dimensional spatial modelling does not replace the need for one-dimensional hydraulic analyses in ecological Reserve determinations. As discussed, RiverCAD is a graphical modelling environment providing an interface for one-dimensional non-uniform hydraulic analyses (eg. HEC-RAS). For lower level Reserve determinations (eg. Rapid III and Intermediate), resource constraints generally require the assumption of one-dimensional uniform flow conditions and the use of basic resistance equations (eg. Manning, Darcy-Weisbach or Chezy). At the Comprehensive level, 3d spatial modelling is only undertaken for selected river sites, and also where more accurate hydraulic characterisations can justify the additional resources required. The application of one-dimensional hydraulic analyses and standard hydraulic data (Figs 7.1 and 7.2 and Table 7.1) therefore remains a basic requirement of the Reserve determination procedure. The section following describes the development of software to assist with such hydraulic analyses, for presentation of results, and to provide integration with other research initiatives, particularly Hughes (2004).

7.4 Development of Hydraulics Software to Assist Reserve Determinations

The ongoing development and refinement of ecological flow assessment methods (eg. O'Keefe *et al*, 2002; O'Keeffe and Hughes, 2004) has indicated that the value of hydraulics can be improved by better integration with other components. This includes an extension of the traditional hydraulic component involving the prediction of basic hydraulic parameters (eg. velocity, depth, etc), to the interpretation of overall hydraulic habitat, as presented in Section 7.2 on the discussion of an index of hydraulic habitat. The use of 3d spatial modelling, as described in Section 7.3, enhances the integration of hydraulics with biological components (eg. vegetation and spatial distribution of depth). Linking hydraulic and hydrological analyses will further benefit ecological flow determination.

During Reserve assessments, it has become evident that there is a need to further develop hydraulics software to:

- assist with the analysis of data, particularly for lower levels of determination where limited measured data are available (ie. Rapid and Intermediate),
- streamline the presentation of results,
- provide greater conformity in the modelling approaches being used, and
- provide a system (data-base) for storing hydraulic information.

The framework for the hydraulic Reserve model, HERR (Hydraulics for the Ecological Rivers Reserve), has been developed to address these requirements, and is discussed in this section. The model is coded in Delphi and is designed for integration with SPATSIM (SPatial And Time Series Information Modelling), which was developed at the Institute for Water Research, Rhodes University (Hughes, 2004). HERR may be executed as an application of SPATSIM. It is envisaged that the framework for HERR developed in this project will be refined during various ongoing projects (eg. WRC Project no.K5/1508 "Eco-hydraulic modelling in river systems"). The framework for HERR has been developed jointly by the CWE and the IWR[1] (Rhodes University).

Figure 7.15 shows the main form. It consists of a main menu (*site, cross-section, analysis and view*), a description of the river and site names and cross-section number; tabulated cross-sectional data (which may be manipulated); hydraulic data including both recorded/measured (date, discharge, stage and slope) and calculated cross-sectional parameters (average velocity and maximum depth, and resistance coefficients according to Manning (n), Chezy (C) and Darcy-Weisbach (f); synthesized hydraulic data (for the purpose of extending measured rating values), which require estimates of the resistance coefficient and slope corresponding to a given specified maximum depth to compute discharge (as well as average velocity and stage). The form also displays a plot of the cross-sectional profile used for viewing any measured or synthesized water level. The main geometric determinants (stage, maximum depth, perimeter and area) are listed alongside the cross-section. Additionally, the regression coefficients for a

[1] Prof. Denis Hughes assisted with linking the HERR input/output data to the SPATSIM data-base, and is involved with further development and refinement of the HERR software. For further information see the web page www.ru.ac.za/iwr/software/spatsim.html.

rating function given by the form of equation 7.11 (Birkhead and James, 1998) are listed on the main form.

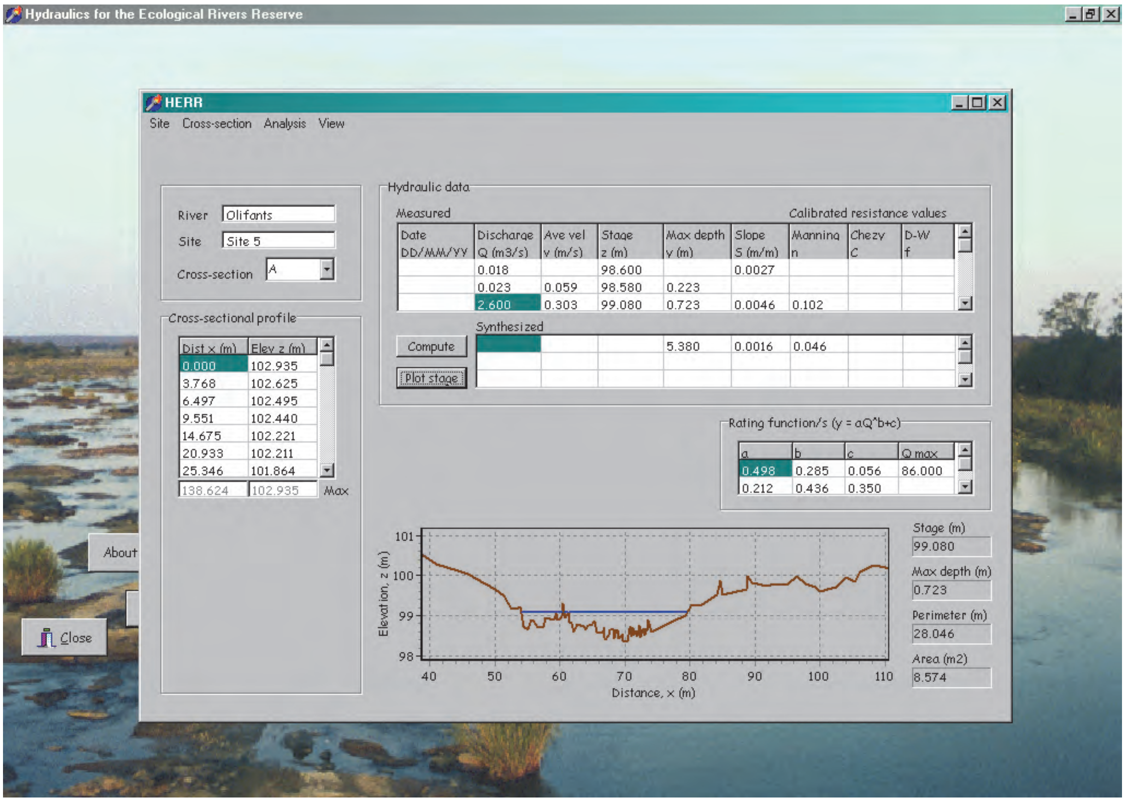

Figure 7.1 The main form in HERR

$$y = aQ^b + c \qquad 7.11$$

in which y is the maximum flow depth (m), Q is the discharge (m^3/s), and a, b and c are regression coefficients.

The software is being further developed to incorporate curve-fitting software to allow the regression coefficients in the rating function (equation 7.11) to be computed, providing a seamless hydraulic modelling environment. Provision is made for this application in the *analysis/rating* drop-down menu. The main menu items contain further drop-down menus. The drop-down menus under *site* include: *new, load from file, load from data-base save to file and save to data-base*. These allow a new site to be established and the data to be loaded from or saved to text files as well as the SPATSIM data-base. The *cross-section* drop-down menu includes: *add* and *delete* for adding or deleting cross-sections to or from the site, and *add profile* for loading (and overwriting existing) cross-sectional profile data. The view menu includes the tasks: *cross-section* and *data-base*. The *view/cross-section* is based on a previous version of the hydraulic display software developed for the Lesotho-Highlands IFR in 1999, and displays water levels for up to six flows on the cross-sectional profiles. The hydraulic parameter values of the maximum and average depths, perimeter and average velocity are also listed. The *data-base* sub-menu is provided for further development of this software (see below). The remaining item on the *analysis* drop-down menu is *depth-frequency,* which launches the depth-frequency form given in Fig. 7.16.

The form in Fig. 7.16 provides the window for undertaking the depth-frequency analysis described in Section 7.2.3.1. The input data required are either the maximum depth or discharge, with the corresponding variable calculated using the rating function (equation 7.11). The user selects distance increments into which the cross-sectional profile is divided, as well as the depth class interval used in the frequency analysis. The results are tabulated using the frequency of occurrence for each depth class and cumulative values, and displayed graphically using a bar chart.

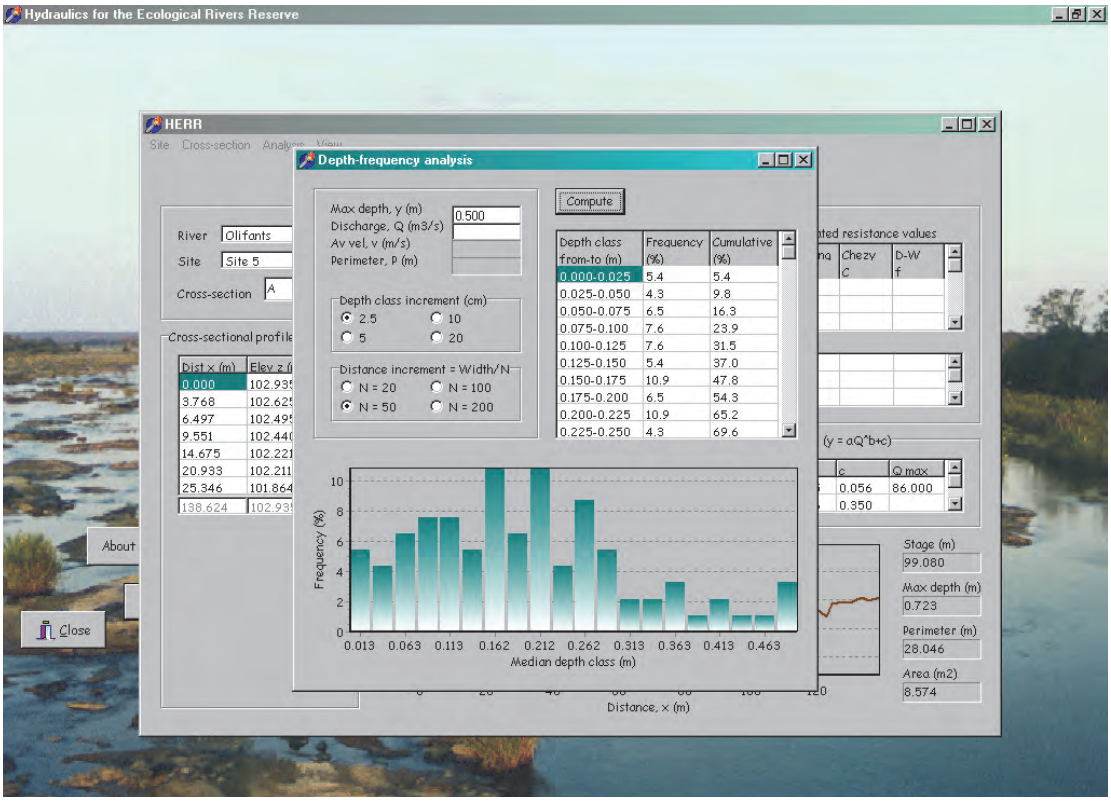

Figure 7.16 Depth-frequency analysis form

The framework for HERR was developed in this project. Ongoing development and refinement of this software will provide a modelling and data storage environment designed specifically for hydraulic analyses for Reserve determinations in South Africa. These developments include:

- Integration of hydraulic analyses and graphical display with hydrological information. These include, for example, the animated display of stage levels on cross-sectional profiles using different discharge time-series (eg. natural, historical, recommended flow regimes corresponding to different ecological categories, and managed flow scenarios). Automated analyses and visual display of duration curves (eg. depth, velocity and wetted perimeter) for various flow regimes. These provide valuable information to assess changes in hydraulic determinants resulting from modified flow regimes.
- Collation and inclusion of hydraulics data from previous IFR and Reserve studies. This will assist with the estimation of resistance coefficients, particularly in Reserve studies involving limited data collection (ie. Rapid and Intermediate determinations). This need has been provided for in a related project commissioned by the WRC (Project no. K5/1508: "Ecohydraulic modelling in river systems")
- Inclusion of probability models for predicting typical velocity distributions (presented in Section 7.2.3.2).
- Inclusion of new forms of resistance equations for large-scale roughness, typical of Reserve determination sites.

7.5 Conclusions

The overall aim of this project has been to further develop the role of hydraulic in assessing ecological Reserves for rivers. This chapter contributions to this main objective through the use of "hydraulic indices" which are defined in terms of hydraulic habitat types for biota; the use of hydraulic analyses, coupled with digital terrain modelling and the mapping of substrate and vegetation, to compliment standard hydraulic information used in Reserve determinations; and the development of hydraulic software to assist analyses and provide integration with other components of the ecological Reserve.

The purpose of a “hydraulic index” is to provide a means for describing, in quantitative terms, the integrated hydraulic characteristics of a river reach, site or channel cross-section, in terms that are meaningful for ecologists to assess the response of biota to changes in flow. The use of general hydraulic indices as surrogates for hydraulic habitat is limited. This is because different biota respond to different constituents of the hydraulic regime, and also at different spatial scales. The Flow Stressor-Response method developed by O’Keeffe *et al* (2002) guides the evaluation of ecological consequences to modified flow regimes using an index to score flow-relates stress. The assessment of hydraulic habitat is implicit in the method, but made explicit through the use of habitat types (or categories) that broadly describe hydraulic habitat for biota (fish and macroinvertebrates). The use of habitat types has been developed within the framework of the FS-R method, but may also be used in holistic flow determination methods that require a semi-quantitative assessment of habitat suitability and abundance. The use of rule-based models for describing habitat conditions and biotic response shows promise, and deserves further investigation for ecological flow assessments. Statistical methods for predicting characteristic velocity distributions enhance the standard hydraulic data used in ecological Reserve studies.

In South Africa, ecological flow determinations have relied on hydraulic information derived for two-dimensional cross-sections and single rating relationships. Three-dimensional spatial models are being used to provide more accurate characterisations of the physical and hydraulic templates, and improve the confidence in the assessments. The value of a GIS based modelling approach has been established in Reserve studies. The unsatisfactory application of hydraulic analysis, however, has resulted in the alternative use of one-dimensional hydraulic modelling in combination with digital terrain modelling. Further developments should re-introduce the use of GIS for post-processing and statistical analyses of hydraulic results.

The framework for the hydraulic Reserve model, HERR (Hydraulic for the Ecological Rivers Reserve) has been developed to address various requirements highlighted during Reserve assessments, including, the need for software to assist with the analysis of data, particularly for lower levels of determination where limited measured data are available; to streamline the presentation of results; to provide greater conformity in the modelling approaches being used; and to provide a data-base for storing hydraulic information generated in ecological Reserve determinations.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

8.1 Conclusions

The purpose of this project was to improve hydraulic input for ecological Reserve determination in South Africa, by providing guidance for the hydraulic analyses necessary to relate a flow regime, in terms of discharge, to biotic response in a river.

The major contributions of this research are described in the following paragraphs.

Hydraulic analyses required in the ecological Reserve determination are focused on the low-flow component of the hydrological regime, and sites are often characterized by large-scale roughness. Hydraulics under such conditions is complicated, and existing approaches for its description are inadequate (Chapter 4). New resistance equations distinguishing between large-scale and intermediate-scale roughness influences have therefore been developed (Chapter 6). The equations have been tested using experimental and field data, and have shown good results. This development will contribute to setting the Reserve at rapid and intermediate levels of determination when hydraulic data are limited.

A framework for a hydraulic reserve model, HERR, has been developed to address various requirements highlighted during Reserve assessments, including the need for software to assist with the analysis of data (particularly for lower levels of determination where limited measured data are available), to streamline the presentation of results, to provide greater conformity in the modelling approaches being used, and to provide a database for storing hydraulic information generated in ecological Reserve determinations.

Indices for rating hydraulic habitat suitability have been widely used and reported in the literature, but are usually dimensionless, and give no indication of absolute values of depth or velocity; they cannot therefore be used to assess the suitability of hydraulic characteristics for biota (Chapter 7). It is important that hydraulic characteristics can be translated into describing, in quantitative terms, the integrated hydraulic characteristics of a river reach, site or channel cross-section, in terms that are meaningful for ecologists to assess the response of the biota to changes in flow.

Development of a “hydraulic index” provides a means for describing, in quantitative terms, the integrated hydraulic characteristics of a river reach, site or channel cross-section, in terms that are meaningful for ecologists to assess the response of biota to changes in flow. The assessment of hydraulic habitat through the use of habitat types (or categories) that broadly describe hydraulic habitat for biota (fish and macroinvertebrates) is implicit in the Habitat-Flow Stressor-Response (H-FS-R) method (O’Keeffe *et al*, 2002) that guides the evaluation of ecological consequences to modified flow regimes using an index to score flow-relates stress.

An aim of this research was to extend existing hydraulic approaches to provide information on habitat availability at sites by incorporating three-dimensional physical mapping and employing hydroinformatics techniques based on digital terrain models (DTMs) and geographical information systems (GISs). The geomorphological method of Wadeson and Rowntree (in press) for describing discharge-related changes in instream habitat using hydraulic biotope mapping to assist ecological Reserve determination was reviewed as a possible basis for addressing this aim. Short-comings of this approach are discussed in Chapter 7. To provide more accurate characterizations of the physical and hydraulic templates, and to improve the confidence in the environmental flow assessment at a comprehensive level of the Reserve determination, an approach to three-dimensional spatial modelling incorporating one-dimensional hydraulic analysis in combination with digital terrain modelling has been therefore favoured in Reserve studies (Chapter 7). A suite of three modelling tools, QuickSurf, RiverCAD and HECRAS, has been used for this purpose. This approach has already been used with success in the hydraulic study of Nyl River Floodplain (Birkhead et al, 2004). Further developments should re-introduce the use of GIS for post-processing and statistical analyses of hydraulic results.

8.2 Recommendations for Further Research

General application of the proposed equations (6.6) and (6.11) for estimating resistance with intermediate bed roughness sizes requires

- estimation of the large scale resistance coefficient F as a simple function of the bed material size characteristics, and
- further verification of the proposed coefficient, a, that effects partitioning of the influences of the large and small roughness scales on flow resistance.

Ongoing development and refinement of HERR will provide facilities for

- integration of hydraulic analyses and graphical display with hydrological information,
- collation and inclusion of hydraulics data from previous IFR and Reserve studies,
- inclusion of probability models for predicting typical velocity distributions, and
- inclusion of new forms of resistance equations for large-scale roughness, typical of Reserve determination sites.

An ecological Reserve determination requires estimation of instream flow, which will maintain the aquatic habitats. The link between the aquatic habitats and the stream flow has been found through hydraulic modelling. Aquatic habitats required for different life-history stages can be determined by flow velocity and flow depth. However average depth and velocity can't describe the diversity of cross-sectional hydraulics. Further research in modelling of cross-sectional velocity distribution for a given discharge is therefore required for recommending ecological flows for fish and macroinvertebrates.

Hydraulic habitat for macroinvertebrates is related to a near-bed flow regime determined by the substrate configuration and its influence on flow patterns and velocity in the near bed region. There are a number of different flow zones where velocities are different (Young, 1996). It was suggested that benthic macroinvertebrate communities may be influenced by turbulence rather than directly by velocities and associated drag forces (Bouckaert and Davis, 1998). In this connection future research related to the near-bed flow is suggested.

The use of habitat types has been developed within the framework of the H-FS-R method, but may also be used in holistic flow determination methods that require a semi-quantitative assessment of habitat suitability and abundance. The use of rule-based models for describing habitat conditions and biotic response shows promise, and deserves further investigation for ecological flow assessments. Statistical methods for predicting characteristic velocity distributions enhance the standard hydraulic data used in ecological Reserve studies.

In summary, further refinement of the equations, software and methods developed will enhance their applicability for ecological Reserve studies.

Chapter 9

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Appendix

Experimental Data for Flow Resistance Due to Large-scale Roughness

Table 1 Measured Data of Series A Experiments

Density 1		**Spacing =157 mm**					
Test	*Q* (m^3/s)	*y* (m)	*V* (m/s)	*R*	*S*	*n*	*Re*
A2.1	0.00064	0.021	0.081	0.019	0.00571	0.0666	5346
A2.2	0.00097	0.027	0.095	0.024	0.00571	0.0658	7842
A2.3	0.00126	0.033	0.100	0.028	0.00571	0.0695	9913
A2.4	0.00186	0.045	0.109	0.036	0.00571	0.0763	13886
A2.5	0.00276	0.066	0.110	0.049	0.00571	0.0919	18914
A3.1	0.00064	0.029	0.058	0.025	0.00114	0.0497	5151
A3.2	0.00088	0.048	0.048	0.038	0.00114	0.0798	6465
A3.3	0.00116	0.050	0.061	0.040	0.00114	0.0644	8450
A3.4	0.00160	0.064	0.066	0.048	0.00114	0.0676	11058
A3.5	0.00214	0.094	0.060	0.063	0.00114	0.0893	13189
A4.1	0.00014	0.014	0.025	0.013	0.00057	0.0521	1161
A4.2	0.00048	0.040	0.032	0.033	0.00057	0.0778	3661
A4.3	0.00110	0.067	0.043	0.050	0.00057	0.0745	7516
A4.4	0.00111	0.078	0.037	0.055	0.00057	0.0929	7240
Density 2		**Spacing =314 mm**					
Test	*Q* (m^3/s)	*y* (m)	*V* (m/s)	*R*	*S*	*n*	*Re*
A5.1	0.000511	0.010	0.134	0.010	0.00571	0.0252	4482
A5.2	0.00142	0.021	0.178	0.019	0.00571	0.0301	11840
A5.3	0.00221	0.030	0.194	0.026	0.00571	0.0342	17608
A5.4	0.00359	0.048	0.197	0.038	0.00571	0.0437	26448
A5.5	0.00564	0.060	0.247	0.046	0.00571	0.0390	39572
A6.1	0.000480	0.019	0.066	0.017	0.00114	0.0339	4029
A6.2	0.00101	0.03	0.089	0.026	0.00114	0.0333	8062
A6.3	0.00173	0.044	0.103	0.036	0.00114	0.0355	12940
A6.4	0.00252	0.062	0.107	0.047	0.00114	0.0410	17516
A6.5	0.00359	0.084	0.112	0.058	0.00114	0.0451	22973
A7.1	0.000165	0.016	0.027	0.015	0.00057	0.0529	1405
A7.2	0.00054	0.034	0.042	0.029	0.00057	0.0535	4245
A7.3	0.00092	0.038	0.064	0.032	0.00057	0.0375	7079
A7.4	0.00121	0.047	0.068	0.038	0.00057	0.0397	8935
A7.5	0.00186	0.065	0.075	0.048	0.00057	0.0422	12769

Table 2 Measured Data of Series B Experiments – Density 1

Test	Q (m^3/s)	y (m)	V (m/s)	R	S	n	Re
Basic resistance			**Rough bed**				
B1.1	0.006	0.0495	0.319	0.039	0.0022	0.0170	43951
B1.2	0.0112	0.072	0.409	0.052	0.0022	0.0160	74997
B1.3	0.0154	0.0875	0.463	0.060	0.0022	0.0155	97361
B1.4	0.0197	0.102	0.508	0.066	0.0022	0.0151	118361
B2.1	0.0155	0.070	0.584	0.051	0.0045	0.0158	104800
B2.2	0.0174	0.080	0.571	0.056	0.0045	0.0172	112867
B2.3	0.0235	0.095	0.651	0.063	0.0045	0.0164	144598
B2.4	0.0280	0.108	0.682	0.069	0.0045	0.0165	164662
Density 1	**Spacing =150 mm**		**Rough bed**				
B3.1	0.00042	0.015	0.074	0.014	0.0045	0.0521	3596
B3.2	0.00200	0.052	0.102	0.041	0.0045	0.0774	14529
B3.3	0.00276	0.066	0.110	0.049	0.0045	0.0822	18892
B3.4	0.00389	0.091	0.112	0.062	0.0045	0.0929	24287
B3.5	0.00597	0.113	0.140	0.071	0.0045	0.0821	34624
B3.6	0.01090	0.146	0.196	0.083	0.0045	0.0647	56913
B3.7	0.01890	0.181	0.276	0.093	0.0045	0.0498	89495
Density 1	**Spacing =150 mm**		**Smooth bed**				
B4.1	0.00025	0.020	0.033	0.018	0.00163	0.0832	2091
B4.2	0.00095	0.048	0.052	0.039	0.00163	0.0889	6994
B4.3	0.00135	0.060	0.059	0.046	0.00163	0.0870	9474
B4.4	0.00180	0.085	0.056	0.059	0.00163	0.1100	11471
B4.5	0.00235	0.105	0.059	0.067	0.00163	0.1130	13999
B4.6	0.00320	0.123	0.069	0.074	0.00163	0.1040	17965
B4.7	0.00510	0.144	0.093	0.082	0.00163	0.0819	26764
B4.8	0.00635	0.160	0.104	0.087	0.00163	0.0760	31802
B4.9	0.00775	0.185	0.110	0.094	0.00163	0.0756	36257
B4.10	0.00965	0.200	0.127	0.097	0.00163	0.0672	43432
B5.1	0.00030	0.011	0.075	0.010	0.0073	0.0526	2625
B5.2	0.00135	0.034	0.104	0.029	0.0073	0.0778	10562
B5.3	0.00325	0.065	0.132	0.048	0.0073	0.0858	22382
B5.4	0.00380	0.076	0.132	0.054	0.0073	0.0926	25086
B5.6	0.00570	0.105	0.144	0.067	0.0073	0.0986	33956

Table 3 Measured Data of Series B Experiments – Density 2

Test	*Q* (m^3/s)	*y* (m)	*V* (m/s)	*R*	*S*	*n*	*Re*
Density 2	**Spacing =100 mm**		**Rough bed**				
B6.1	0.00088	0.038	0.061	0.032	0.0045	0.1102	6771
B6.2	0.00145	0.058	0.066	0.044	0.0045	0.1261	10292
B6.3	0.00166	0.062	0.071	0.046	0.0045	0.1220	11580
B6.4	0.00240	0.084	0.075	0.058	0.0045	0.1351	15332
B6.5	0.00339	0.109	0.082	0.069	0.0045	0.1382	19891
B6.6	0.00673	0.143	0.124	0.082	0.0045	0.1019	35457
B6.7	0.01840	0.218	0.223	0.101	0.0045	0.0655	79216
Density 2	**Spacing =100 mm**		**Smooth bed**				
B7.1	0.00030	0.029	0.027	0.025	0.00163	0.1301	2399
B7.2	0.00050	0.044	0.030	0.036	0.00163	0.1464	3749
B7.3	0.00065	0.067	0.026	0.050	0.00163	0.2133	4437
B7.4	0.00095	0.082	0.030	0.057	0.00163	0.1968	6127
B7.5	0.00115	0.102	0.030	0.066	0.00163	0.2237	6905
B7.6	0.00235	0.120	0.052	0.073	0.00163	0.1367	13321
B7.7	0.00430	0.150	0.076	0.084	0.00163	0.1020	22220
B7.8	0.00710	0.169	0.111	0.089	0.00163	0.0727	34745
B7.9	0.00860	0.185	0.123	0.094	0.00163	0.0678	40288
B7.10	0.01050	0.204	0.136	0.098	0.00163	0.0634	46784
B8.1	0.00025	0.015	0.043	0.014	0.0045	0.0908	2137
B8.2	0.00085	0.039	0.058	0.032	0.0045	0.1176	6519
B8.3	0.00150	0.060	0.066	0.045	0.0045	0.1293	10537
B8.4	0.00190	0.072	0.069	0.052	0.0045	0.1359	12706
B8.5	0.00250	0.097	0.068	0.064	0.0045	0.1586	15282
B9.1	0.00060	0.026	0.061	0.023	0.0073	0.1133	4873
B9.2	0.00115	0.040	0.076	0.033	0.0073	0.1163	8772
B9.3	0.00200	0.062	0.085	0.047	0.0073	0.1306	13924
B9.4	0.00280	0.084	0.088	0.058	0.0073	0.1463	17928
B9.5	0.00350	0.103	0.090	0.067	0.0073	0.1567	20975

Table 4 Measured Data of Series B Experiments – Density 3

Density 3	**Spacing =75 mm**		**Rough bed**				
Test	*Q* (m^3/s)	*y* (m)	*V* (m/s)	*R*	*S*	*n*	*Re*
B10.1	0.00026	0.020	0.033	0.018	0.0022	0.0987	2127
B10.2	0.00053	0.046	0.030	0.037	0.0022	0.1742	3933
B10.3	0.00075	0.064	0.031	0.048	0.0022	0.1982	5190
B10.4	0.00206	0.116	0.047	0.072	0.0022	0.1743	11801
B10.5	0.00443	0.143	0.082	0.081	0.0022	0.1077	23374
B10.6	0.00826	0.171	0.127	0.090	0.0022	0.0739	40186
B11.1	0.00072	0.042	0.045	0.035	0.0045	0.1584	5440
B11.2	0.00080	0.047	0.045	0.038	0.0045	0.1683	5922
B11.3	0.00090	0.053	0.045	0.041	0.0045	0.1797	6498
B11.4	0.00100	0.056	0.047	0.043	0.0045	0.1773	7123
B11.5	0.00160	0.088	0.048	0.060	0.0045	0.2152	10097
B11.6	0.00176	0.096	0.048	0.064	0.0045	0.2203	10815
B11.7	0.00617	0.141	0.115	0.081	0.0045	0.1090	32703
B11.8	0.01426	0.182	0.206	0.093	0.0045	0.0668	67251
Density 3	**Spacing =75 mm**		**Smooth bed**				
B12.1	0.00020	0.024	0.022	0.022	0.00163	0.1438	1638
B12.2	0.00035	0.047	0.020	0.038	0.00163	0.2315	2591
B12.3	0.00045	0.061	0.019	0.046	0.00163	0.2693	3142
B12.4	0.00065	0.082	0.021	0.057	0.00163	0.2876	4192
B12.5	0.00070	0.100	0.018	0.066	0.00163	0.3574	4231
B12.6	0.00180	0.123	0.039	0.074	0.00163	0.1848	10105
B12.7	0.00425	0.147	0.076	0.083	0.00163	0.1011	22109
B12.8	0.00570	0.164	0.091	0.088	0.00163	0.0873	28249
B12.9	0.00730	0.182	0.105	0.093	0.00163	0.0786	34404
B12.10	0.01140	0.201	0.149	0.098	0.00163	0.0575	51118
B13.1	0.0003	0.026	0.030	0.023	0.0045	0.1807	2434
B13.2	0.00050	0.042	0.031	0.034	0.0045	0.2264	3781
B13.3	0.00110	0.068	0.043	0.050	0.0045	0.2117	7494
B13.4	0.00135	0.085	0.042	0.059	0.0045	0.2414	8620
B13.5	0.00160	0.106	0.040	0.068	0.0045	0.2795	9499
B14.1	0.00030	0.021	0.038	0.019	0.0073	0.1582	2497
B14.2	0.00090	0.045	0.052	0.037	0.0073	0.1797	6712
B14.3	0.00130	0.063	0.054	0.047	0.0073	0.2070	9006
B14.4	0.00190	0.084	0.059	0.058	0.0073	0.2166	12154
B14.5	0.00235	0.106	0.059	0.068	0.0073	0.2424	13952

Table 5 Measured Data of Series C Experiments

Test	*Q* (m^3/s)	*y* (m)	*V* (m/s)	*R*	*S*	*n*	*Re*
C1.1	0.01472	0.291	0.133	0.115	0.0012	0.0615	53689
C1.2	0.02287	0.346	0.174	0.123	0.0012	0.0492	74856
C1.3	0.03139	0.403	0.205	0.129	0.0012	0.0432	92867
C1.4	0.04285	0.523	0.216	0.139	0.0012	0.0432	105435
C1.5	0.05324	0.624	0.225	0.146	0.0012	0.0427	114746
C1.6	0.06278	0.698	0.237	0.149	0.0012	0.0412	124032
C2.1	0.00011	0.029	0.010	0.025	0.0024	0.4251	873
C2.2	0.00018	0.038	0.013	0.031	0.0024	0.3828	1397
C2.3	0.00042	0.059	0.019	0.045	0.0024	0.3245	2985
C2.4	0.00140	0.076	0.049	0.054	0.0024	0.1439	9221
C2.5	0.01460	0.191	0.201	0.095	0.0024	0.0508	67228
C2.6	0.02250	0.237	0.250	0.105	0.0024	0.0438	92444
C2.7	0.03110	0.272	0.301	0.112	0.0024	0.0378	118098
C2.8	0.04080	0.335	0.321	0.121	0.0024	0.0374	136341
C2.9	0.05330	0.388	0.362	0.128	0.0024	0.0343	161780
C2.10	0.06250	0.435	0.378	0.132	0.0024	0.0336	175439
C3.1	0.00032	0.04	0.021	0.033	0.0049	0.3414	2448
C3.2	0.00042	0.0485	0.023	0.039	0.0049	0.3487	3110
C3.3	0.00094	0.062	0.040	0.047	0.0049	0.2270	6562
C3.4	0.00145	0.068	0.056	0.050	0.0049	0.1692	9876
C3.5	0.01472	0.156	0.248	0.086	0.0049	0.0548	74637
C3.6	0.02250	0.186	0.318	0.094	0.0049	0.0455	104983
C3.7	0.03110	0.215	0.381	0.101	0.0049	0.0398	134720
C3.8	0.04110	0.252	0.429	0.108	0.0049	0.0371	163134
C3.9	0.05330	0.286	0.490	0.114	0.0049	0.0336	196447
C3.10	0.06250	0.307	0.536	0.117	0.0049	0.0313	220622
C4.1	0.00116	0.066	0.046	0.049	0.00642	0.2328	7920
C4.2	0.00026	0.036	0.019	0.030	0.00642	0.4171	1981
C4.3	0.00016	0.028	0.016	0.024	0.00642	0.4347	1328
C4.4	0.00045	0.043	0.028	0.035	0.00642	0.3110	3395