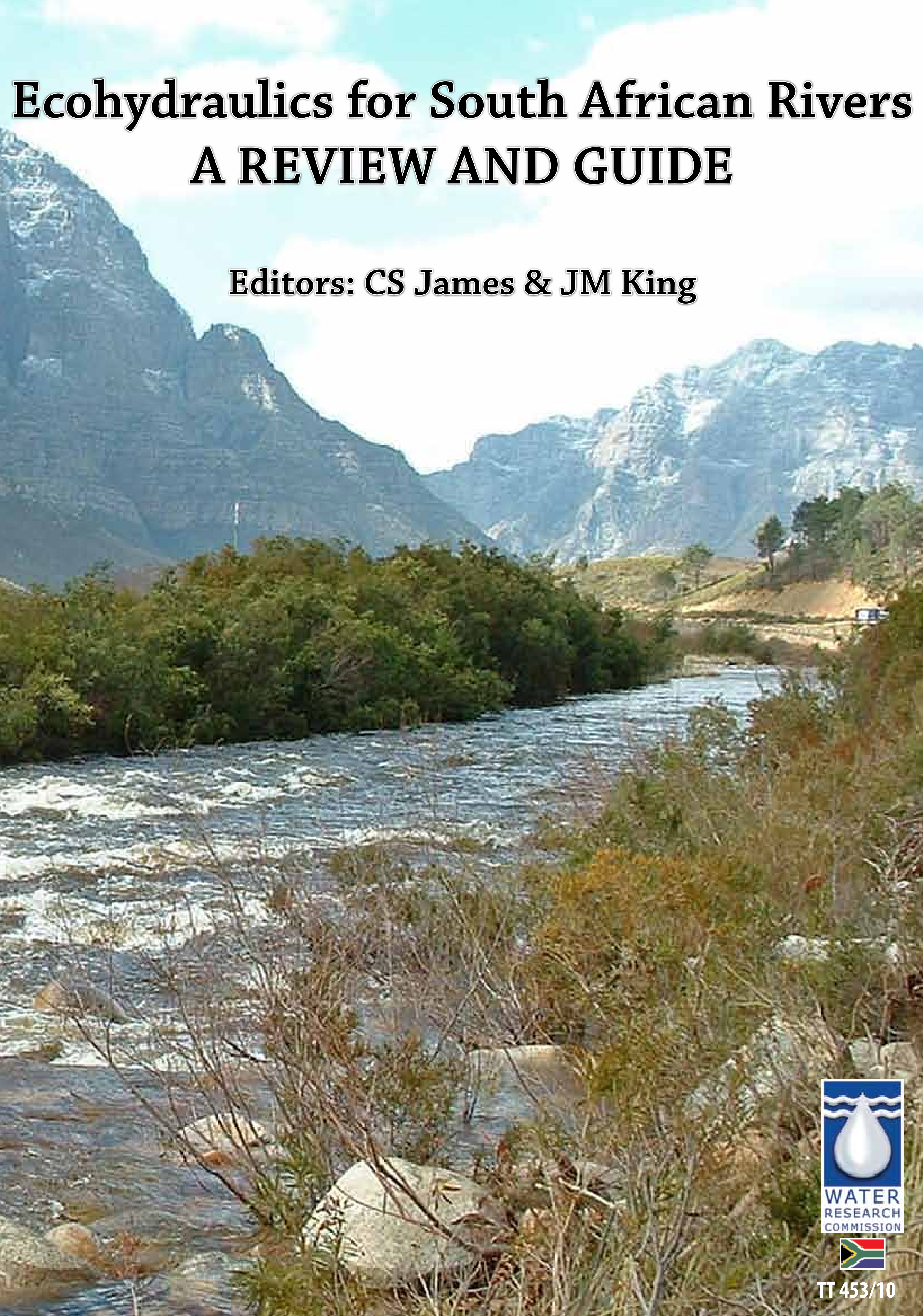

Ecohydraulics for South African Rivers
A REVIEW AND GUIDE

Editors: CS James & JM King

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PREFACE

Ecohydraulics is defined as the study of the linkages between physical processes and ecological responses in rivers, estuaries and wetlands (Centre for Ecohydraulics Research, Univ. Idaho, 2006). Since the early 1990s, the science of ecohydraulics has developed at a rapid pace. This was mainly in response to the need to inform Ecological Water Requirement and river rehabilitation studies aimed at predicting and mitigating the impacts of changes in flow and sediment regimes on river ecosystems. Essentially, these studies assess the magnitude and timing of flows necessary to maintain a river ecosystem in a pre-determined, environmentally acceptable condition, with ecohydraulics providing a tool to characterise the relationship between discharge and the availability of physical (hydraulic) habitat within the river ecosystem. Based on this relationship and an understanding of the hydraulic conditions that are optimal for different species or communities, ecohydraulic modeling is employed to predict how hydraulic conditions in a river might change under different development scenarios and thus, how the aquatic habitat of specific species or communities could be affected.

Over the past almost twenty years in South Africa, a great deal of knowledge on ecohydraulics, related to both research and application, has been gained through several projects involving the Water Research Commission, the Department of Water Affairs and Forestry and other institutions in South Africa. The realisation that this information and knowledge are fragmented and often inconsistent across various knowledge centres and disciplines, e.g. aquatic ecology, riverine vegetation, sedimentation, fluvial morphology and fundamental hydraulics, prompted this project, the objective of which was to provide a synthesis of existing knowledge on ecohydraulics in South Africa in a logical and accessible format. Not only does this document present theories and techniques related to ecohydraulics, it also provides the ecological context and perspective for the application of ecohydraulics and as such builds capacity amongst both engineers and ecologists and contributes towards the effective management of our aquatic environment. Furthermore, as this document provides an overview of the current state of ecohydraulics research in South Africa, it serves as a useful point of reference for identifying and prioritising future research needs for ecohydraulics in South Africa.

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LIST OF ABBREVIATIONS AND ACRONYMS

ATTZ	Aquatic Terrestrial Transition Zone
BBM	Building Block Methodology
BD	Back Dynamic (vegetation) zone
BHNR	Basic Human Needs Reserve
BOIL	Boil (flow type)
BPF	Barely Perceptible Flow (flow type)
BSW	Broken Standing Waves (flow type)
CART	Classification And Regression Tree
CAS	Cascade (flow type)
CES	Conveyance Estimation System
CH	Chute (flow type)
CSI	Combined Suitability Index
DCM	Divided Channel Method
DRIFT	Downstream Response to Imposed Flow Transformation
DSLF	Dry Season Low Flow
DTM	Digital Terrain Model
DWAF	Department of Water Affairs and Forestry (South Africa)
EC	Ecological Category
EFR	Environmental Flow Requirement
EIA	Environmental Impact Assessment
ER	Ecological Reserve
EWR	Ecological Water Requirement
FAq	Floating Aquatic (vegetation) zone
FBB	Fast/ Boulder and Bedrock (flow class)
FCS	Fast/Coarse Sediment (flow class)
FD	Fast/Deep (flow class)
FDC	Flow Duration Curve
FF	Free Falling (flow type)
FFS	Fast/Fine Sediment (flow class)
FI	Fast/Intermediate (flow class)
FMP	Flow Management Plan
FRF	Fast Riffle Flow (flow type)
FS	Fast/Shallow (flow class)
FS-R	Flow Stressor-Response
FVS	Fast/Very Shallow (flow class)

GPS	Global Positioning System
HABFLO	Habitat-Flow Simulation Model (software)
HB	Hydraulic Biotope
HEC-RAS	Hydrologic Engineering Center – River Analysis System (software)
HFSR	Habitat Flow Stressor Response
HSC	Habitat Suitability Criteria
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
LD	Lower Dynamic (vegetation) zone
LDM	Lateral Distribution Method
LIDAR	LIght Detection And Ranging
LWB	Lower Wetbank (vegetation) zone
MVEG	Marginal Vegetation
NF	No Flow (flow type)
NWA	South African National Water Act (No 36 of 1998)
PHABSIM	Physical HABitat SImulation Model
POM	Particulate Organic Matter
RAq	Rooted Aquatic (vegetation) zone
RCC	River Continuum Concept
RDM	Resource Directed Measures Directorate of the DWAF
RES	Riverine Ecosystem Synthesis
River2D	Two-dimensional flow model (software)
RS	Rippled Surface (flow type)
RU	Resource Unit
SBB	Slow/ Boulder and Bedrock (flow class)
SBT	Smooth Boundary Turbulent (flow type)
SCS	Slow/Coarse Sediment (flow class)
SD	Slow/Deep (flow class)
SFS	Slow/Fine Sediment (flow class)
SRF	Slow Riffle Flow (flow type)
SS	Slow/Shallow (flow class)
STR	Stream (flow type)
SVS	Slow/Very Shallow (flow class)
TR	Trickle (flow type)
TS	Tree-Shrub (vegetation) zone
USW	Undular Standing Waves (flow type)
UWB	Upper Wetbank (vegetation) zone
VFBB	Very Fast/Boulder and Bedrock (flow class)
VFCS	Very Fast/Coarse Sediment (flow class)
VFFS	Very Fast/Fine Sediment (flow class)
VSBB	Very Slow/Boulder and Bedrock (flow class)
VSCS	Very Slow/Coarse Sediment (flow class) (flow class)
VSFS	Very Slow/Fine Sediment (flow class)
WAR	Water Allocation Reform
WRC	Water Research Commission (South Africa)
WRCS	Water Resource Classification System

WSLF	Wet Season Low Flow
WUA	Weighted Usable Area
1-D	One-Dimensional
2-D	Two-Dimensional
3-D	Three-Dimensional

GLOSSARY

Glossary items for Part II

Aquatic-Terrestrial Transition Zone (ATTZ)	Any ecotone between aquatic and terrestrial environments – often used to describe river floodplains that are subject to inundation and drying cycles, and thus a *moving* ATTZ.
Benthic	Referring to the bottom of an aquatic system.
Benthos	The invertebrates inhabiting the surface layers of the substratum or bed of the aquatic ecosystem.
Biotope	Also Hydraulic biotope – spatial unit in a classification of geomorphological features of a river. Hydraulic biotopes are at the finest scale of the geomorphological classification of rivers and refer to small areas (1-10 sq. meters) characterised by specific water flow characteristics and substratum conditions.
Clast	A rock fragment or grain resulting from the breakdown of larger rocks.
Community	Populations of different species inhabiting the same geographical area that are linked by mutually dependent interactions.
Disturbance	Any relatively discrete event that causes mortality or displacement of populations and opens up new space in an ecosystem for colonisation by other organisms, examples are floods, fires, droughts, chemical spills.
Diversity	The variety of species in a sample, community, or area, including both the number or richness of species and the degree to which any species are numerically dominant.
Ecology	The study of the inter-relationships between organisms and their environment and each other.
Ecotone	The boundary line or transitional area between two ecosystems, usually characterised by higher diversity as elements of both ecosystems overlap.
Flow regime	The timing, magnitude, frequency and duration of different magnitude flows

	over periods from hours to decades.
Fluvial geomorphology	The study of water-shaped landforms.
Habitat	The combination of all the environmental conditions and all the resources in an area that result in the presence, survival and reproduction of a species in that area. See Box 2.1.
Hydrology	The study of the inter-relationships and interactions between water and its environment in the hydrological cycle.
Hyporheos	The spaces between rocks and among sediment particles below the surface layers in a wet river channel.
Instar	Refers to developmental stages during the life of immature insects (larvae), separated by a moult of their exoskeleton.
Intermediate Disturbance Hypothesis (IDH)	The hypothesis that species diversity is greatest in ecosystems subjected to intermediate levels of disturbance. Ecosystems that have little disturbance or those that have very frequent disturbances are predicted to be species-poor.
Invertebrate	Animals without backbones.
Keystone species	Organisms that play dominant roles in an ecosystem and affect many other organisms. The removal of a keystone predator from an ecosystem causes a reduction of the species diversity among its former prey.
Limnophilic	Affiliated with standing water.
Macroinvertebrate	Invertebrates large enough to be seen with the naked eye.
Meioinvertebrate	Invertebrates inhabiting the interstitial spaces of the stream bed or hyporheic zone, which are smaller than 1 millimeter but larger than 0.1 millimeter.
Metabolism	The total chemical activity occurring within living organisms.
Microhabitat	The specific conditions and resources in a portion of an animal’s habitat, examined at a finer scale.
Natural Flow-Regime Paradigm	The view that the natural flow regime provides a paradigm in which to understand diversity and ecological integrity among rivers, and the key to sound management.
Nutrient cycling / nutrient spiralling	The process whereby nutrients are incorporated into living matter, mineralised and released through decay, and incorporated again; nutrient cycling in lakes takes place in a closed system, whilst in rivers, as a result of downstream

	transport of mineralised nutrients, the process is referred to as nutrient. spiralling.
Osmoregulation	Regulation of the osmotic pressure in animals through control of the amount of water and/or salts in the body.
Patch / patch dynamics	Idea that communities occur across a mosaic of different areas (patches) within which non-biological disturbances (such as climate) and biological interactions proceed.
Pelagic	Organisms inhabiting the open water, including plankton (floating or drifting small plants and animals) and nekton (free-swimming organisms like fish).
Refugium	An area of survival in an otherwise changing landscape.
Resilience	The ability of a population or community to recover from disturbance; refers to the speed of recovery.
Resistance	The ability of a species or community to withstand the effects of disturbance; refers to degree to which species persist through a disturbance unharmed.
Rheophilic	Affiliated with flowing water.
Riparian	Along or on the banks of rivers and streams.
River Continuum Concept (RCC)	A view of river ecosystems that emphasises the gradients of physical and chemical conditions that are continuously modified from source to sea, resulting in longitudinal gradients in biological communities that inhabit the river.
Stream hydraulics	The pattern of flow through a stream reach, in terms of water depths, water velocities and wetted area in relation to discharge.
Stream order	An indication of the size of a river according to the number of tributaries it has; a stream with no tributaries has an order of 1; two tributaries joining form a stream of order 2; two streams of order 2 form a 3rd order stream ....
Stream power	Rate of energy expenditure at a given location in a river system.
Substrate	The surface or medium that serves as a base upon which something grows; often incorrectly used to refer to substratum.
Substratum	The material that forms the bottom of a river or lake or the sea.
Target species	The species under examination in a study.
Taxon (plural taxa)	A definite unit in the classification of plants and animals: a taxonomic unit.

Thalweg	The deepest path along a stream channel.

Glossary items for Part III

Alluvial channel:	A channel formed within the sediment (alluvium) that it transports.
Bed disturbance:	The initiation of movement of individual bed particles within the bed material mixture.
Bed forms:	The recognised geometries of mobile channel beds as deformed by flowing water.
Bed load:	Sediment transported in continuous or intermittent contact with the river bed.
Compound channel:	Also known as a 'two-stage' channel. A channel that has a main section accommodating normal flows and a flood plain on one or both sides that is inundated during flood flows.
Conveyance:	A measure of the discharge capacity of a river channel; technically defined as $K = Q/(S_f^{0.5})$, where Q is discharge and S_f is the energy gradient.
Discharge:	The volumetric flow rate in a channel, quantified in m^3/s or l/s.
Drag:	The force exerted on an object by flow around it, arising from surface resistance and the unsymmetrical pressure distribution resulting from flow separation.
Drag coefficient:	A dimensionless, empirically determined coefficient relating the force of drag to flow, fluid and object characteristics; defined by $C_D = F_D/(A\rho V^2/2)$, where F_D is the drag force, A is the object's projected area, ρ is the fluid density and V is the flow velocity.
Effective discharge:	The value of discharge associated with most of the bed material transport in a river, and therefore associated with its morphological characteristics.
Emergent vegetation:	Vegetation with plants extending through the water surface.
Flow regime:	The temporal occurrence of discharge in a river.
Flushing flow:	The discharge required to remove fine sediments from the interstices in cobble and gravel river beds.
Form resistance:	Flow resistance arising from the effects of bed or channel form; associated predominantly with drag forces arising from flow separation and the consequent pressure distribution around objects or channel irregularities.

Froude Number:	A dimensionless number characterizing the effects of gravity on flow conditions, and hence used to distinguish between subcritical and supercritical flows. Calculated as $Fr = Q^2B/gA^3$ for cross sections, or approximately as $Fr = V/(gD)^{0.5}$ for wide, shallow channels or local conditions, where Q is discharge, B is the surface flow width, g is gravitational acceleration, D is flow depth, A is the cross-sectional flow area and V is the average flow velocity.
Hydraulic radius:	The ratio of the cross-sectional flow area of a channel to its wetted perimeter. It is often approximated by the flow depth for wide, shallow channels.
Intermediate-scale roughness:	The situation where the size of roughness elements on a channel bed is between about 1 and 1/10 of the flow depth.
Laminar flow:	Low velocity flow dominated by the effects of water viscosity; characterized by Reynolds numbers less than about 2000.
Large-scale roughness:	The situation where the roughness elements on a channel bed protrude through the water surface.
Mobile bed:	A channel bed of relatively fine material (usually sand) that deforms under the influence of flowing water.
Nikuradse roughness:	A boundary roughness height used for calibration of resistance equations; it is related to, but not equal to, the physical height of roughness elements.
Non-uniform flow:	Flow with hydraulic characteristics that vary in space (*cf.* ‘Uniform flow’).
Rating relationship:	See ‘Stage-discharge relationship’.
Regime theory:	The association of an alluvial river’s equilibrium morphological characteristics with flow and sediment properties and valley slope.
Resistance, Flow resistance:	The effect of the physical characteristics of a conduit on the relationship between discharge, flow depth and velocity.
Resistance coefficient:	An empirical coefficient in a resistance equation that accounts for the resistance effects of channel characteristics and energy-dissipating processes at higher resolution than described by the equation.
Reynolds Number:	A dimensionless number characterizing the effects of fluid viscosity on flow conditions. Calculated for channels as $Re = 4VR/\nu$, where V is the average velocity, R is the hydraulic radius and ν is the kinematic viscosity of the fluid.
Roughness:	The physical size of the roughness elements in a channel; sometimes inappropriately used for a resistance coefficient.

Shear Reynolds Number:	A dimensionless number characterizing the effects of boundary roughness and near-bed flow conditions on flow characteristics. Calculated for channels as $Re^* = u_* k_s / \nu$ where u_* is the shear velocity, k_s is the Nikuradse roughness and ν is the kinematic viscosity of the fluid.
Shear velocity:	A representation of boundary shear stress in velocity dimensions; calculated as $u_* = (\tau_o/\rho)^{0.5}$, where τ_o is the boundary shear stress and ρ is the fluid density.
Sinuosity:	A measure of the extent of channel meandering; calculated as the distance between two points in the channel measured along the channel divided by the straight-line distance between the two points.
Small-scale roughness:	The situation where the roughness elements on a channel bed are smaller than about 1/10 of the flow depth.
Stage:	The height of the water surface above a selected datum; equal to the flow depth if the datum is selected as the lowest point of the channel bed.
Stage-discharge relationship:	(Also rating relationship.) A relationship, either graphical or mathematical, that describes the variation of water level with discharge in a channel.
Steady flow:	Flow where hydraulic characteristics do not vary with time. The definition is usually loosely applied to ignore turbulent fluctuations.
Submerged vegetation:	Vegetation with plants totally below the water surface.
Substrate:	Generally, a substance that underlies another or on which processes take place. Here it represents the material constituting the river bed. Ecologists use ‘substratum’ synonymously.
Surface resistance:	Flow resistance arising from the effect of boundary shear stress.
Suspended load:	Sediment transported and maintained within the flow by turbulence.
Turbulent flow:	Flow in which the effects of fluid viscosity are small and eddying or mixing occurs over a wide range of scales; characterized by values of Reynolds number greater than about 4000. Turbulent flow is sub-classified as hydraulically smooth (where a layer of viscous flow exists at the boundary), hydraulically rough (where the size of boundary roughness prevents formation of a viscous flow layer) and transitional (an inconsistent state between hydraulically smooth and rough). These conditions are characterized by values of the Shear Reynolds number.

Uniform flow:	Flow where hydraulic characteristics are the same at all locations. The definition is usually used loosely to imply constancy between cross sections; it is rarely applied rigorously, as it is an ideal condition that rarely occurs.
Unsteady flow:	Flow where hydraulic conditions vary with time (*cf*. ‘Steady flow’).
Volumetric hydraulic radius:	The ratio of the volume of water in a defined element of flow to the wetted area of channel boundary. For practical purposes this can be approximated by the mean flow depth, i.e. the vertical distance between the water surface and the mean bed level.
Wash load:	Very fine sediment transported by the flow and not significantly represented in the bed material.
Wetted perimeter:	The length of channel cross section in contact with water.

PART I : INTRODUCTION

1. INTRODUCTION

1.1 Background

The relationship between discharge and the availability of physical (hydraulic) habitat within the river ecosystem, coupled with an understanding of the hydraulic conditions that are optimal for different species or communities, constitute the essence of ecohydraulics. Ecohydraulic modeling is employed to predict how hydraulic conditions in a watercourse might change under different development scenarios and thus, how the aquatic habitat of specific species or communities could be affected. Researchers in South Africa have been extensively involved with ecohydraulics research since the early 1990s. Furthermore, over the last decade, particularly since the promulgation of the National Water Act (No. 36 of 1998), various ecohydraulic models and theories have been applied as part of multi-disciplinary water resource projects in southern Africa.

The motivation for this Water Research Commission project stemmed from the realisation that the extensive knowledge and information on ecohydraulics that is currently available in South Africa, constituting two decades of learning, are fragmented and often inconsistent across various knowledge centres and disciplines, e.g. aquatic ecology, riverine vegetation, sedimentation, fluvial morphology and fundamental hydraulics. The key objective of this project therefore entailed a synthesis of existing knowledge on ecohydraulics in South Africa in the form of a Review and Guide document. Not only does this Guide present theories and techniques related to ecohydraulics, it also provides the ecological context and perspective for the application of ecohydraulics and as such builds capacity amongst both engineers and ecologists and contributes towards the effective management of our aquatic environment. Furthermore, as the Guide provides an overview of the current state of ecohydraulics research in South Africa, it serves as a useful point of reference for identifying and prioritising future research needs for ecohydraulics in South Africa.

It is of importance to note that the techniques and theory presented in this document deal exclusively with ecology and ecohydraulics within a river context, with the intention that environmental hydraulics in its broader sense, which typically include biological and chemical aspects in lakes, estuaries and wetlands, will be addressed in subsequent research projects. Furthermore, it is necessary to point out that the hydraulic theory that is presented in this document assumes that the user of this Guide will have a graduate level of understanding of river hydraulics. However, the content is presented in such a way as to ensure that water resource practitioners and managers as well as researchers across a wide spectrum of disciplines, should find the document informative and useful.

1.2 Objectives

The project objectives are summarised below:

i. Compile a database and provide a synthesis of existing published literature on environmental hydraulics in South Africa
ii. Solicit current South African knowledge, experiences and practices through wide stakeholder consultation, by means of a workshop or a once-off conference on ecohydraulics

iii. Investigate and report on hydraulic theories and applied river hydraulics within a South African ecohydraulics context and present this information in the form of a guide on how current ecohydraulics challenges in reserve determinations and river rehabilitation studies could be addressed

The deliverable under the first objective entailed the compilation of an electronic database of existing environmental hydraulics research as well as a synthesis thereof in terms of research areas covered and potential areas for further research. The focus of the database was intentionally on research conducted in South Africa instead of on international research. The Synthesis Report and electronic database are included on the CD attached to this Report.

The purpose of the second objective was to ensure that existing information and practices relating to ecohydraulics applications in South Africa are incorporated into the final document and this was achieved by means of a workshop attended by 17 specialists. A Workshop Report is also included on the CD attached to this Report.

The third objective culminated in this report. Although the report focuses on a review of existing ecohydraulic theory and applications in South Africa and serves as a guide for its application, the report includes a comprehensive introductory section on river ecology, which provides the ecological context for ecohydraulics and serves to highlight ecological issues in relation to ecohydraulics.

1.3 Report Layout

This report has been structured to consist of four parts:

I. Introduction

This Part, which includes Chapter 1, serves as an introduction to the project and describes the study objectives and the report layout.

II. Ecological Context

The ecological context for this report is described in Part II, which includes Chapters 2 to 5. Chapter 2 describes the classification of South African rivers at a range of scales with specific emphasis on the physical habitat. Chapter 3 outlines those attributes of river ecosystems that should be taken into account when managing and predicting ecosystem changes in a river and includes a hierarchical ecosystem definition along with descriptions of survival adaptations of river-dwelling organisms and biotic-abiotic links in river ecosystems. Chapter 4 focuses on the description of hydraulic habitat in rivers and specifically deals with the relationship between flow, habitat, channel morphology and vegetation. Finally, Chapter 5 serves as a link between Part II and Part III and presents key issues and challenges with regard to ecohydraulics from an ecological perspective.

III. Ecohydraulics in Practice

Part III concerns hydraulic theories, techniques and applications related to ecohydraulics and consists of Chapters 6 to 10. Chapter 6 provides an introduction to ecohydraulics, presents guidance on selecting appropriate models for describing the hydraulic habitat at an ecologically relevant scale and describes the role of water in driving river ecosystems. Chapter 7 presents ways of describing flow resistance in rivers – an essential input to deterministic hydraulic modeling at all levels of resolution. Chapter 8 identifies hydraulic characteristics associated with channel form and substrate condition and provides techniques for estimating maintenance flows. Chapter 9 presents current best practice for carrying out the hydraulic analyses necessary for determining the Ecological Reserve for rivers in South Africa, while Chapter 10 describes some engineering measures for river rehabilitation and impact mitigation of river structures.

IV. Conclusion

Conclusions and recommendations are provided in Part IV, Chapter 11.

PART II : ECOLOGICAL CONTEXT

2. PATTERNS AND PROCESSES IN THE RIVER LANDSCAPE

GR Ractliffe, BR Paxton and JM King

2.1 Introduction

In its passage across the landscape and through time, water gives rise to the distinctive features, and is subject to the recurrent cycles, that are commonly associated with river systems. The change in the quantity of water and in its sediment load from headwaters to sea, the repeated sequences of fast and slow moving water, and the annual advance and retreat of water across floodplains are some of the key processes that contribute to the diversity of landforms found in rivers. As water flows downstream it has the ability to do work that is expended in downward movement, in heat, in turbulence and in sound. Much of this work, however, goes into shaping the bed and the banks of the channel through which the water flows. Thus, distinctive fluvial features in the river landscape (or 'riverscape'; *sensu* Ward, 1998) such as meanders, floodplains, cobble bars, sand bars, islands, deltas and beaches, arise from this interaction of water and sediment. These features, together with the water flowing through, over and around them, provide the physical living space – the habitat – for organisms. Southwood (1988) described physical habitat as the ‘template on which evolution forges characteristic life-history strategies’ and so it is important to understand the nature physical aspects of the riverscape in order to be able to predict what types of organisms will occur there.

Two outstanding features of river systems are, firstly, that they are spatially heterogeneous and therefore provide a variety of different types of habitats for organisms to live in, and secondly, that they are temporally dynamic – they change over daily, yearly, decadal and longer time frames. The sections that follow consider, from an ecologist's point of view, some of the concepts that have informed thinking around the structural and functional characteristics of rivers, viewed at a range of scales.

2.2 Broad-scale spatial pattern

2.2.1 South African bioregions and ecoregions

South Africa has a widely varying geology and geomorphology, the result of millions of years of continental movement, and cycles of uplift and erosion. Its climate ranges from semi-arid and arid, to humid, with a gradient of decreasing rainfall from east to west. These two factors result in a diverse range of ecosystems, including river ecosystems. Most of the country's rivers flow seasonally or intermittently, particularly in the arid central and western parts of the country, and there are few large river systems compared with the rest of Africa and the world. Many South African rivers are short, steep coastal rivers, deeply incised in the landscape as a result of continental uplift.

River organisms have evolved over millenia to cope with their abiotic and biotic environment, and as a result the communities of plants and animals in any one river tend to be structured, rather than random, entities (Lamouroux *et al.*, 2002). Whilst the types of species that are able to persist in any given river system are those with suitable morphological, behavioral and life-history attributes (Chapter 3), at a larger scale the suite of potential species in a river is constrained by the regional species pool, which is a result of the biogeographical history of the region, its climate, geology and topography, and the ability of species to disperse between catchments.

Classifying geographical areas into similar units allows for generalisations regarding their physical and biological properties and their ecological functioning, which is an essential part of understanding the nature of South African inland waters. Eekhout *et al*. (1997) used available distributional information on three groups of riverine organisms (riparian plants, invertebrates and fish) at a tertiary catchment level to delineate biogeographical regions for South Africa. This was augmented with detailed information on physiography to produce 18 bioregions for South Africa (Brown *et al*., 1996).

In a different approach, Allanson *et al*. (1990) defined and described five limnological regions within the southern African sub-continent, based on geomorphological, geochemical and climatological features. Each limnological region would be expected to influence biogeographical process in a particular way, and thus these regions also describe broad suites or typical assemblages of species that form the regional species pools.

More recently, ecoregional typing of the South African landscape was used to create an Ecoregions map for South Africa, Lesotho and Swaziland (Figure 2-1) using multiple geographical variables. These included physiography, climate, geology and soils; and potential natural vegetation. At the broadest level (Level 1 of the Ecoregion classification) the key variables used in the typing were terrain morphological classes and natural vegetation – the latter is considered to be an integrated reflection of variables such as climate, rainfall and geology. Summarised information per ecoregion for each of the 31 described in this process included:

- terrain morphology
- main vegetation types
- mean annual precipitation
- coefficient of variation of mean annual precipitation
- drainage density
- stream frequency
- slope
- median annual simulated runoff
- mean annual temperature.

Ecoregions provide a broad indication of the types of rivers, and types of plants and animal communities, one could expect to find in any part of the country. As such, the Ecoregion classification has become the basis for the grouping of rivers for a range of water-resource management purposes, including the River Health Programme reference site classification (Dallas and Fowler, 2000), the National Water Resource Classification (Brown *et al*., 2007) and the National Wetland Classification (Ewart-Smith *et al*., 2006).

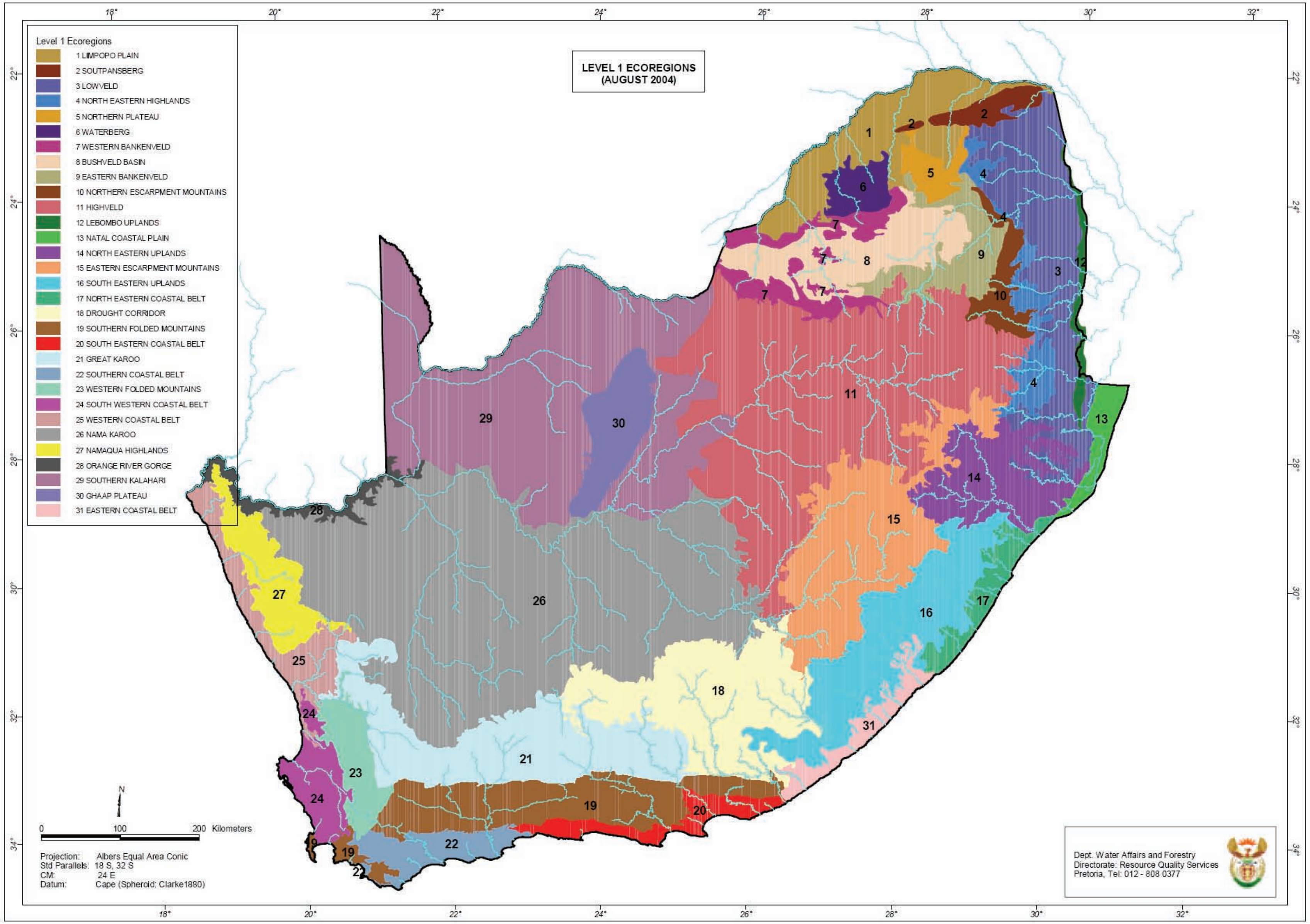

Figure 2-1 Ecoregions of South Africa, Lesotho and Swaziland (from Kleynhans et al.,2005)

2.2.2 Catchment signatures

Lower levels of classification than Ecoregion have been proposed, the first suggestion being the grouping together of river reaches within an Ecoregion based on features such as altitude and gradient. Thus, for instance, within any one Ecoregion, all mountain streams could group together, and all foothill sections of rivers could be in another group. But the influence of the biogeographical history, and perhaps other forces, on a catchment remains apparent at scales smaller than Ecoregion, and simply grouping river zones per Ecoregion may be too simplistic. In a study of 18 Western Cape headwater rivers, King and Schael (2001) found that invertebrate communities exhibited distinctive river and catchment signatures in community structure that could not be predicted on the basis of either catchment or river-zone abiotic variables – invertebrate samples clustered by catchment and then by river, and then by the general nature of the riverbed (bedrock or alluvial); only after that did they group, at a lower level, by river zone. It seems that the species pool of any one river is dependent on ancient patterns of colonisation and extinction, and on subtle catchment differences. Thus between the Ecoregions and the finer-scale, within-river differences recognized by longitudinal river zones should be inserted at two other levels of classification – that of the catchment itself, and then the distinction between bedrock and alluvial rivers. The assumption that all mountain streams, for instance, within an Ecoregion support the same community of plants and animals ignores a level of biodiversity that is still only partially understood but needs to be recognized in management decisions. At the fourth level of classification, after ecoregion, catchment, and riverbed type, there is clear structuring of river communities within any one river that is driven by the abiotic environment.

2.3 The four-dimensional river

Rivers can be thought of as four-dimensional systems, since they vary in space (three dimensions) as well as time (the fourth dimension). These interact to drive behavioural and evolutionary responses in living organisms (Figure 2-2; Ward, 1989). The sections that follow discuss in more detail each of these dimensions: the longitudinal (upstream downstream linkages), vertical (river channel and river bed/groundwater interface), lateral (channel-riparian zone/floodplain system) and temporal.

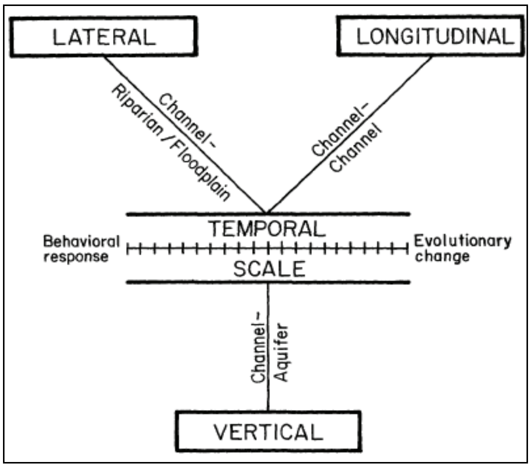

Figure 2-2 The three spatial dimensions of a river system: longitudinal, lateral and vertical change through different time scales (the temporal dimension) to produce behavioural responses in living organisms over the short term and evolutionary changes in the long term (Ward, 1989)

2.3.1 The longitudinal dimension

Longitudinal zones and hydrogeomorphological patches

One of the defining characteristics of river systems is that they are longitudinal features of the landscape that act as one-way conveyor belts, transporting energy and materials downstream to the sea (Kondolf, 1997). The classical approach to partitioning individual river systems has been to divide them into a continuous set of zones from source to sea (e.g. headwater, foothill and lowland) (Hawkes, 1975) along the river's longitudinal profile. Each zone is characterised by its hillslope gradient, which is in turn shaped by the geology and topography of the catchment. Other variables that may change per zone are channel width, volume of Mean Annual Runoff (MAR), hydraulic characteristics, substratum particle size, water quality, temperature and more.

Most rivers begin in mountain source zones, where numerous seeps and springs feed mountain headwater streams. These are characterised by straight channels with steep gradients, and large bed material such as boulders delivered from mass wasting of the surrounding hillslopes or by exposure in a well-scoured river bed. Erosional processes predominate and waterfalls, cascades and plunge pools are typical features of the river channel, forming the step-pool morphology characteristic of this zone (Table 2-1 and Figure 2-3). As the gradient decreases in the foothills and the water loses its sediment-transport capacity, larger bed particles from upstream are deposited on the bed and along the banks. The discharge increases because more water is contributed from additional tributaries in the wider catchment and a typical riffle-run-riffle sequence of morphological features replaces the step-pool channel morphology of the headwater zone (Figure 2-4). Further downstream, in the lowlands, depositional features such as meanders and extensive floodplain areas become more common, the gradient declines still further and finer sediments such as sand and silt settle out of the current (Figure 2-5). Finally the river reaches the sea at the estuary, the upstream boundary of which is defined by the limit of tidal influence. Although a common pattern is the orderly transition of one zone into another along the course of the river, the zones may be repeated or appear in a different order along a river system depending on local topographic conditions.

Table 2-1 Ecological definitions of longitudinal zones for South African rivers (after Rowntree and Wadeson, 1999)

Zone	Definition
Mountain headwater stream	Very steep-gradient stream (>0.1) in V-notched canyons, dominated by vertical flow over bedrock and boulders, with waterfalls and plunge pools. Approximately equal vertical and horizontal flow components. Straight channel. First or second order stream. Reach types: step-pool
Mountain stream	Steep-gradient stream (0.01-0.1) in steep-sided valley, dominated by cobbles and boulders, with local coarse gravel in quiet areas. Confined valley floor and low sinuosity. Second order stream. Reach type: plane-bed
Foothill	Moderately steep (0.005-0.01), cobble-bed river in gentle-gradient valleys with confined valley floor and moderate sinuosity. Narrow floodplains of sand and gravel. Second to third order river. Reach type: run-riffle. Runs and riffles about the same length
Transitional	Lower-gradient (0.001-0.005) sand and gravel river with local bedrock intrusions. Moderately sinuous channel pattern. Wide gentle valley slopes with well-developed floodplain adjacent to the river. Middle order river. Reach types: planar bedrock, regime. Pools much longer than riffles/rapids
Lowland	Low-gradient (0.0001-0.001), pool-like, sand-bed river in very broad valley associated with extensive floodplains and meanders. High sinuosity, fully-developed meandering channel pattern, with large silt deposits. Reach type: regime

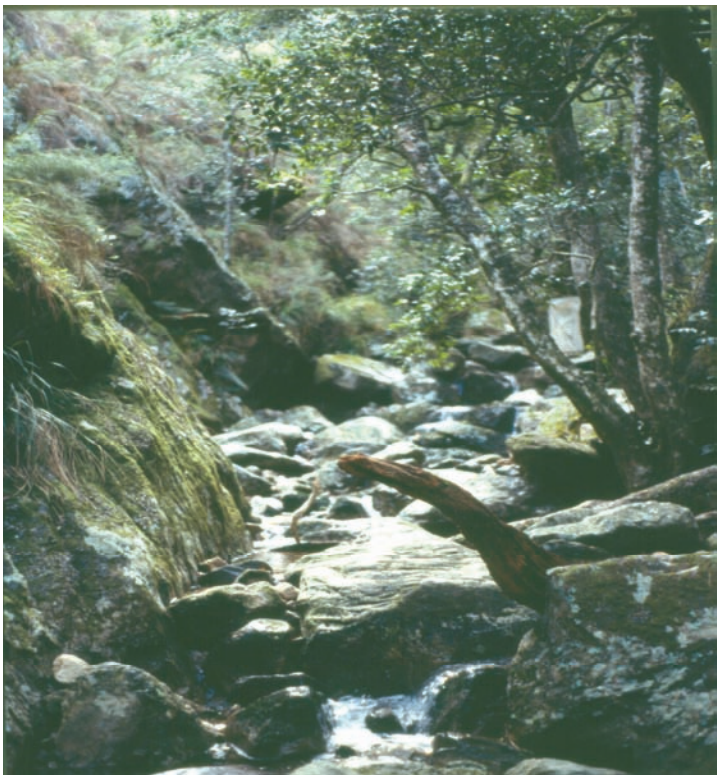

Figure 2-3 A mountain headwater stream

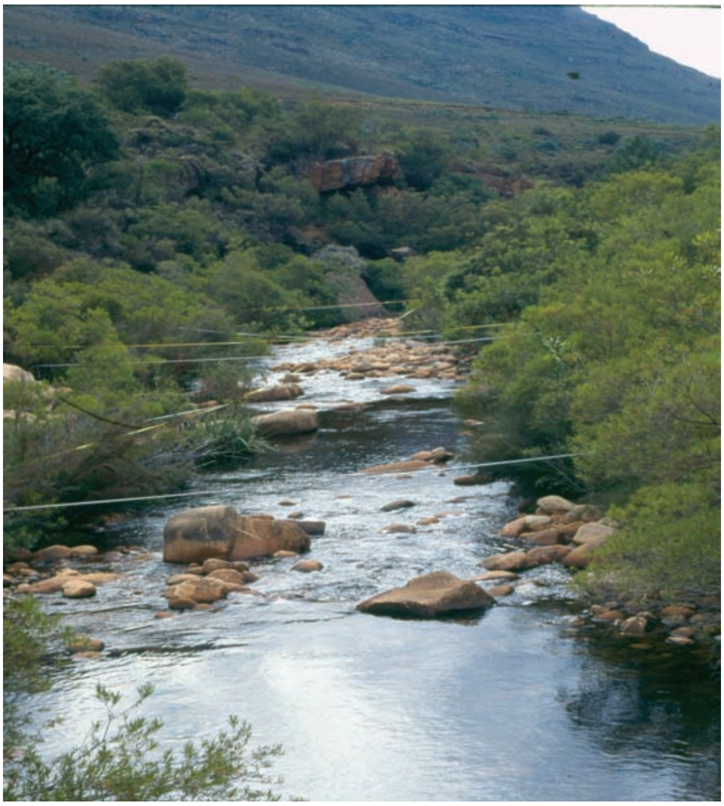

Figure 2-4 A foothill run-riffle sequence

Figure 2-5 A transitional zone

River zones should not be viewed as a series of isolated zonal units in 'a string of pearls (Davies and Day, 1998). Unlike terrestrial ecosystems that are bound in some way by geographical, climatic or other factors, river zones are largely unbounded – what happens in the headwaters and the catchment as a whole can affect processes tens, if not hundreds or even thousands of kilometres downstream. The River Continuum Concept (RCC) (Vannote *et al.*, 1980) was one of most influential ecological frameworks to emerge from the classical river zonation approach (Hawkes, 1975) helping to shape conceptual thinking about river ecosystem functioning for more than a decade. Fundamental to the RCC is the view that the physical stream network is in a state of dynamic equilibrium, with predictable and continuous downstream adjustments in the relationships between stream width, depth, velocity and sediment load. This adjustment takes place because of the way in which kinetic energy is utilised. Following the laws of conservation of energy, rivers tend toward a uniform expenditure of energy along their lengths. The shape of the longitudinal profile of a river is a consequence of this uniform expenditure of energy. Energy expenditure, or Stream Power, is a product of the slope (S) and the discharge (Q). In the upper reaches, the gradient or slope (S) is generally high and the discharge (Q) low, but as the discharge increases with distance downstream, the slope declines to maintain the constancy of QS (Gordon *et al.*, 2004).

In addition to these physical changes, the RCC predicts that changes in catchment topography, hydrology, water chemistry and water temperature between the headwaters and the estuary will result in predictable longitudinal changes in the production, input, transport, utilisation and storage of food and that these changes will be reflected in the river communities. Thus, in the headwater zone food, primarily in the form of rotting leaves, is contributed by the riparian zone. As the river widens downstream and riparian trees cover less of the open water, there is a gradual shift in the sources of food within the river, with an increase in instream organic production by aquatic plants. The RCC predicts that in response to this, distinct and predictable species replacements of animals will occur along the length of the river in order to maximize the efficient use of food. Aquatic invertebrates, for instance, may be grouped by their means of feeding and type of food into Functional Feeding Groups such as predators, grazers and filter feeders. The RCC predicts that in upstream reaches, the invertebrate community will be dominated by species adapted to shred large particles of organic material such as leaves, whilst further downstream these species will largely disappear, replaced by species that graze algae from rocks and vegetation or that filter fine organic material drifting downstream from the upper reaches.

For the most part rivers do conform to these patterns. In South Africa, as far back as the 1950s, one of the pioneers of river ecology in South Africa, Prof. Arthur Harrison, demonstrated invertebrate community changes in the Berg River in the Western Cape that corresponded to the geomorphological river zones later described for this river, which included mountain headwall; stony foothill; gravel foothill and lower river (Harrison and Elsworth, 1958). Since then, similar zonation patterns have been described in many South African rivers for riparian vegetation, invertebrates and fish.

A river's longitudinal profile, however, may not consist of a fixed sequence of downstream changes. In recent years, concepts more sensitive to the individual character of rivers have been developed, which are able to account for discontinuities in the typical sequence. The Riverine Ecosystem Synthesis (RES) (Thorp *et al.*, 2006), for example, views rivers as longitudinal arrays of relatively large hydrogeomorphological patches that are defined by particular combinations of hydrological and geomorphological conditions and not by a one-way gradient of physical conditions down the length of a river. Unlike the longitudinal zones put forward by Hawkes (1975), these unique hydrogeomorphological patches are not repeated along the length of the river, and, unlike longitudinal zonation patterns, their order of occurrence along the river does not necessarily follow a downstream continuum. Characteristic physical and chemical conditions associated with each type of hydrogeomorphological patch, such as tributary confluences, divergence and convergence areas in braided channels and vegetated islands, provide the template for ecological zonation.

Geomorphological hierarchies

A second way in which to envisage the longitudinal organisation of river ecosystems is through the lens of a geomorphological classification of river reaches. Frissel *et al*. (1986) proposed a hierarchical framework, based on geomorphological properties, for classifying river environments. The spatial scales of this hierarchy range from the catchment-level drainage network to a single substratum particle. In this hierarchical view of river systems, each spatial scale in the hierarchy corresponds to a different time scale of change: the lowest hierarchical level with the smallest spatial scale is vulnerable to change over days or even hours and minutes, whilst the highest level with the largest spatial scale changes over geological time.

Following from this, the South African Hierarchical System (Wadeson, 1995; Rowntree and Wadeson, 1999) is a six-tiered hierarchical classification model for South African rivers based on geomorphological features of rivers (Figure 2-6), with spatial units at each level defined as follows:

- **catchment –** the area draining into the stream network
- **zone –** areas within the catchment homogeneous in runoff and sediment production
- **segment** – sections of channel corresponding to each zone through which flows of water and sediment are routed, and therefore where the sediment:discharge ratio is relatively constant
- **reach –** the length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occur within identifiable channel patterns

- **morphological unit –** the basic channel-spanning structures comprising channel morphology, such as pools and riffles (Table 2-2)
- **hydraulic biotope –** small patches characterised by specific flow types (Table 2-3) and substratum conditions.

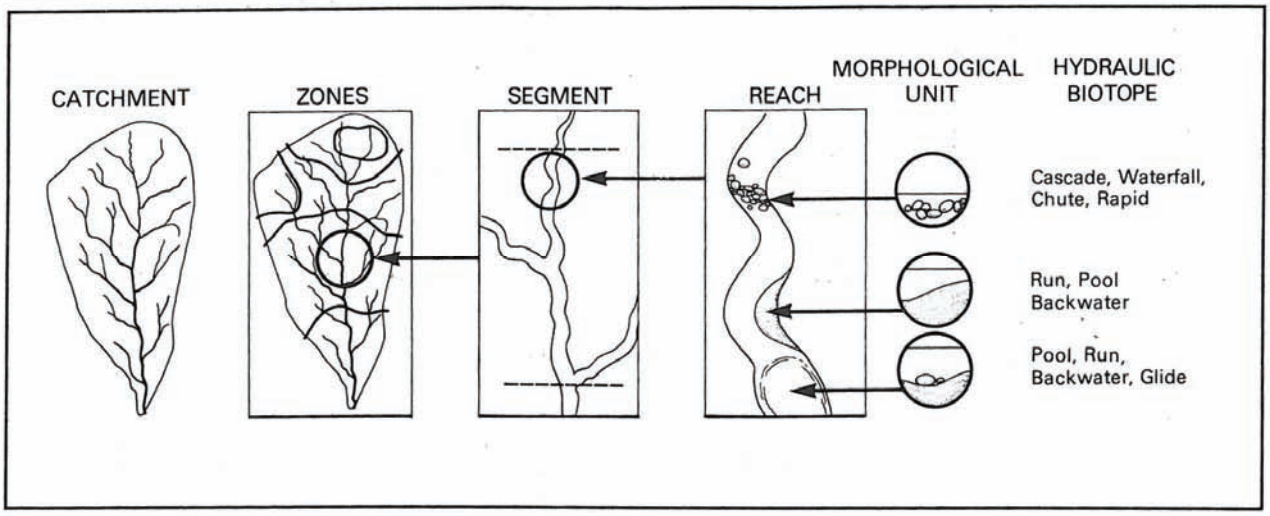

Figure 2-6 The South African hierarchical system (Rowntree and Wadeson, 1999)

According to this classification system, the nature of features at each scale will be determined by the nature of those units higher in the hierarchy. For example, reach characteristics generally either are constrained by bedrock or are free-forming in alluvium (Ward, 1998), and this will determine the extent of river floodplain, sinuosity, substratum size range and more, and thus the possible types and characteristics of morphological units present at the next lower level in the hierarchy.

At the scale of reaches and morphological units, mesohabitats such as riffles (Table 2-2), rapids, pools, cobble and sand bars, beaches, islands and debris snags are evident. Broad groups of riverine fauna may be distinguished at this level. For example, benthic invertebrates such as mayflies and caddisflies are more common in morphological units that are high points in the channel and have shallow water, whereas pelagic invertebrates such as whirligig beetles and zooplankton are more commonly found in pools. Because they are the most mobile organisms in rivers, fish may use a range of morphological unit types: pools for resting, runs for feeding and riffles for spawning. Different species may specialise in certain habitat types, with some spending all their lives in pools, whilst others will be specialist riffle dwellers. In a reach-scale analysis of fish communities on two continents (Europe and North America), Lamouroux *et al.* (2002) demonstrated that geomorphological (pool, riffle, run) and hydraulic (Froude number) descriptors act as important abiotic filters for fish community traits. They showed that in reaches characterised by pools with low Froude numbers, fish communities were dominated by large, deep-bodied and pelagic species, whereas those in reaches characterised by riffles were dominated by strong-swimming, streamlined species that could withstand high shear stress. While not surprising, it nevertheless demonstrates that riverine animal communities are not where they are by chance but are reacting to and structured by their ambient physical conditions. The fact that these trends are found on many continents illustrates that such structuring is fundamental to river ecosystems.

Table 2-2 Definitions of some common morphological units (after Rowntree and Wadeson, 1999; King and Schael, 2001)

Mesohabitat	Definition
Step	Free-falling water over slabs of bedrock or boulders, in step-like arrangements. Average water depth and velocity not distinguishing features
Pool	Channel feature with slow through-flow. Deep relative to channel size with low to zero velocity. All kinds of substratum. Scoured at high flows
Rapid	Tumbling, turbulent flow over bedrock or boulders. Variable water depth, with high to very high velocities, and white water
Run	Moderately fast, fairly smooth flow over any substratum. Water surface rippled, not choppy. High water depth to substratum size ratio. No obvious gradient in water surface
Riffle	Rapid, turbulent flow over cobbles, gravel and small boulders. Water depth shallow relative to bed particle size. Distinct gradient in water surface. Flickering white water
Backwater	Hydraulically detached alcove with no through-flow of water. If connected, water tends to enter and leave via same route. Velocity usually close to zero. Substratum usually sand, silt and debris

This view of rivers adds a further dimension to the classical views expressed in the RCC. Rivers are seen as encompassing a diversity of physical conditions at several different spatial scales, with the arrangement of these nevertheless being governed by the same hydrological and geomorphological drivers as recognized in the RCC. Within the river zones at the reach and morphological unit levels, characteristic animal and plant communities may be associated with the different physical features such as rapids, riffles and pools (Figure 2-6) and, adding to the complexity, any one type of feature is likely to support different communities in different rivers or in different parts of the same river. Overarching all is the major constraint of ecoregions and biogeography: even with suitable habitat, organisms will only occur if a river is in a suitable ecoregion, and if they have been able to move to and establish themselves in that catchment.

At the smallest scale, hydraulic biotopes, or microhabitat patches, range in size from one metre to a few millimetres. Such biotopes form mosaics of habitat (Box 2.1) along the river wetted channel and are categorised by their unique combinations of substratum, and of water depth and velocity manifested as a flow type (Table 2-3). The biotopes are most appropriately viewed as the habitat scale for invertebrate and algal studies, and offer a speedy insight into where different groups of species live: simuliid blackflies on rocks in cascading water, for instance, and caenid mayflies in quiet waters with sediment-covered stones. At this level, the nature of the substratum is important: fish may move in open water, with the nature of the river-bed of small concern except as a source for their food or refuge, but invertebrates are mostly bottom-dwelling and different species are intimately connected to different kinds of substrata and hence to different hydraulic biotopes.

Such a conceptualisation of river environments has complemented another important theoretical concept in understanding how riverine biotas are organised spatially, that of Patch Dynamics (Pickett and White, 1985; Pringle *et al.*, 1988; Townsend, 1989; Wu and Loucks, 1995). This emphasises the study of the spatial arrangement of patches including the juxtaposition of patch types and connectivity between like patches within the riverscape. These are considered to be of substantial importance in maintaining, or constraining, ecosystem functioning. For example, fish migration along a river channel relies on the existence of certain patch types that allow passage in order for the fish to complete this important phase in its life cycle. Waterfalls may preclude some fish from the upper reaches of a river; resting pools between rapids may be essential for long distance migrations; riffles may be too shallow to allow passage; floating mats of algae or vegetation may reduce oxygen levels to such an extent so as to prohibit passage for some species.

Table 2-3 Categories of visually distinct flow types (after Rowntree, 1996; Newson *et al.*, 1998; King and Schael, 2001)

Flow Type	Definition
Free falling (ff)	Water falls vertically without obstruction
Cascade (cas)	Water tumbling down a stepped series of boulders, large cobble or bedrock
Boil (boil)	Water forming bubbles, as in rapidly boiling water; usually below a waterfall or strong chute
Chute (ch)	Water forced between two rocks, usually large cobble or boulders; flowing fast with the fall too low to be considered free falling.
Stream (str)	Water flowing rapidly in a smooth sheet of water; similar to a chute but not forced between two bed elements
Broken standing waves (bsw)	Standing waves present which break at the crest (white water)
Undular standing waves (usw)	Standing waves form at the surface but there is no broken water
Fast riffle flow (frf)	Very shallow, fast, flickering flow, still covering most of the substrata
Rippled surface (rs)	The water surface has regular smooth disturbances which form low transverse ripples across the direction of flow
Slow riffle flow (srf)	Very shallow, slower, flickering flow, still covering most of the substrata
Smooth boundary turbulent (sbt)	The water surface remains smooth; medium to slow streaming flow takes place throughout the water profile; turbulence can be seen as the upward movement of fine suspended particles
Trickle (tr)	Small, slow, shallow flow; when occurring with small or large cobbles, flow is between bed elements with few if any submerged
Barely perceptible flow (bpf)	Smooth surface flow; only perceptible through the movement of floating objects
No flow (nf)	No water movement

Patches are defined as spaces that exist at a range of scales, have relatively uniform conditions and resources and that can be colonised by individuals belonging to different species. In each patch, the outcome of processes such as population growth, foraging or competition can alter the type of patch (for example its biotic composition, or some abiotic characteristics), as well as the dynamics between patches. Because habitat quality also varies between patches, a species must inhabit an area with a mosaic of patch types that will meet its survival, growth and reproductive needs. Each patch will be associated with its own trade-offs: a patch with high food availability, for instance, might also have higher levels of predation or competition, or be in fast flows that require expenditure of much energy. Predictable differences between upstream and downstream patches within streams may exist as a result of the different scales of patchiness, the longitudinal influence of segment and reach characteristics, and disturbance (Townsend, 1989). In this regard, Pringle *et al.* (1988) suggested that concepts such as the RCC are best evaluated by studying changes in characteristics of, and interactions between, patches along a stream continuum.

2.3.2 The vertical dimension – the hidden domain

As important to river systems as the transport of materials longitudinally downstream and laterally between the channel and banks or floodplain is the exchange of energy and materials between the surface water in the main channel and the bed of the river. One of the more recent developments in river ecology has been the linking of groundwater ecology with traditional river ecology. The hyporheos (hypo = below; rheein = flow), or hyporheic zone is immediately beneath the riverbed at the interface between surface runoff and groundwater. This area plays an important role in nutrient cycling – the decomposition and mineralisation of particulate organic matter (POM). Depending on the flow and groundwater-surface water fluxes, much of the organic matter may accumulate in the river bed and be temporarily retained there before being released back into the system in a series of recycling loops. In lakes and terrestrial ecosystems, these loops tend to be closed, whereas in rivers, the moving current transports both decomposing POM and nutrients downstream. The recycling loops in a river are therefore open and the process has been described as 'nutrient spiralling' (Newbold *et al.*, 1982). Macroinvertebrates play an important role in nutrient spiralling, shredding organic matter, consuming nutrients and energy and locking these into biomass in and on the riverbed before releasing them back into the environment either through excretion, drift or death of the organisms.

This simple-sounding process may in fact be more complex. Malard *et al*. (2002) described how the exchange of water, nutrients, organic matter, and organisms between the surface and groundwater of a river channel exert a major influence on temperature, nutrient sources and sinks and ultimately the patchiness of organisms within the streambed sediments (cf. Patch Dynamics Concept). They described down-welling and upwelling flow paths at various scales, including infiltration of water into the hyporheos in areas of high surface pressure, such as the upstream end of a riffle, and upwelling in areas of low surface pressure such as the downstream end of a riffle. In relation to stream patches, hyporheic flow upwelling through short gravel bars may be a source of nitrate to the stream, whereas longer bars would be a sink of nitrate caused by the increased residence time of water in the subsurface area. Fisher *et al.* (1998, in Malard *et al*., 2002) illustrated how the spatial arrangement of sand bars affects nitrogen cycling in a desert stream, and its consequences for patchiness in algal assemblages. Upwelling of nitrate-rich subsurface water at the downstream ends of sand bars stimulates the growth of green algae between floods (Figure 2-7). As algal uptake causes nitrate concentrations in the surface stream to decrease with distance from upwelling zones, green algae are replaced by nitrogen-fixing blue-green algae. Consequently, the distribution and spatial extent of nitrate-consuming patches and nitrogen fixing patches in the surface stream, and their related periphytic flora, are determined in part by the distance between sand bars. This too has implications for the distribution of invertebrate grazers, most of which forage between algal patches.

Box 2.1
What is habitat?

The term habitat is often used loosely to describe the physical attributes of the environment in which organisms live, but studies of the physical environment investigate only some of the characteristics of an organism's habitat because habitat is more than the range of physical conditions present in an environment. A useful definition of habitat is 'the combination of all the environmental conditions and all the resources in an area that result in the presence, survival and reproduction of a species in that area’ (modified from Hall *et al*., 1997). This indicates that a species’ habitat includes structural features (e.g. substratum composition and flow), ambient conditions (e.g. chemistry or temperature), and biotic conditions such as the availability of food (prey), the density of competitors or the presence of predators.

Different species living within an area will always have slightly different habitats – no two species utilise the resources or respond to the conditions pertaining in a place in precisely the same way. If they did, then the principles of competition theory in ecology to dictate that the strength of competition between the two species for exactly the same resources would result in one species annihilating the weaker competitor. As a result of competition between them species may utilise a resource in different ways, such as one feeding by night and the other by day, and their coexistence is predicated upon such finely balanced resource partitioning. Anthropogenic disturbances to ecosystems, such as those associated with pollution, flow alteration or physical change can and usually do cause shifts in the character, quality and suitability of species’ habitats, in terms of both abiotic and biotic conditions. Such changes, subtly or otherwise, alter the presence, survival and reproduction of one or more species, often leading to shifts in community composition, loss of sensitive species and proliferation of pest species.

Because each species responds differently to the pertaining suite of environmental and biotic conditions, the term habitat is, strictly speaking, specific to a species. One thus correctly refers to ‘the habitat of Species A’. In more general terms the term is used, less correctly, for guilds of species, such as ‘fish habitat’, and has little meaning at the level of ‘riverine habitat’ or ‘riparian habitat’. Notwithstanding, physical attributes of the environment such as water velocity and depth are considered to be perhaps the most important features of the habitat of almost all organisms in rivers and these determine, to a major extent, the communities of plants and animals found there. This has lead to the use of the term habitat to refer, incorrectly but persistently, to the physical habitat only. Some authors have addressed this by coining the terms ‘physical habitat’ or ‘hydraulic habitat’ to describe physical features of the environment that support a particular river species. These are the aspects of habitat that are relevant to this document.

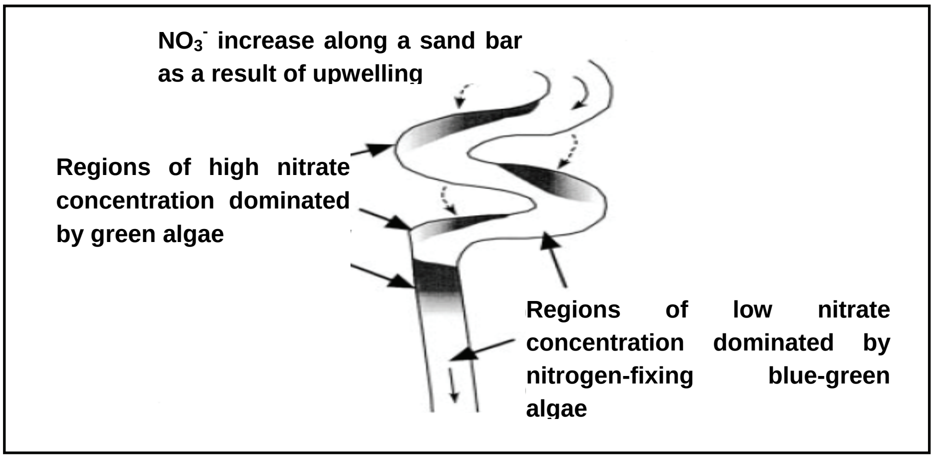

Figure 2-7 Patchiness in nitrate concentrations as a result of the interaction of surface-subsurface water fluxes, as a function of the spatial configuration of sand bars. (After Fisher *et al.*, 1998)

2.3.3 The lateral dimension – beyond the wetted edge

While the longitudinal component of a river's structure is undoubtedly one of its most defining features, its lateral dimension is also important in overall ecosystem functioning. A river ecosystem is more than just the channel from source to sea. Alongside the river, beyond its active channel, may be numerous areas that are intermittently inundated when the river overtops its banks. These areas are rich riverine ecotones, areas transitional between one type of ecosystem (terrestrial) and another (aquatic). They include backwaters, riparian zones, riverine wetlands and floodplains. Together, they comprise a diverse mosaic of landscape elements that varies in topography, in the extent and duration of surface water inundation, in water quality and in plant and animal communities.

Sometimes referred to as the Aquatic Terrestrial Transition Zone (ATTZ) (Junk *et al*., 1989), floodplains exchange energy, materials, plants and animals with the channel. There is a strong temporal dimension to the ATTZ, with its functionality being dependent on the seasonal fluctuations in flow and the overtopping of the banks of the river during floods. Inundation may occur through the lateral spread of water from the channel as it overtops banks, or from some upstream point where flows spilled over and then spread downstream over the floodplain. The flooding of formerly terrestrial habitats creates a new aquatic environment, where life is stimulated by the nutrients released from drowned vegetation, by quietly-moving water and by abundant refuge areas. During inundation large amounts of organic carbon and inorganic nutrients carried by the river are also deposited onto the floodplain, further stimulating a period of extensive productivity of plant communities and the animal communities they support. The productivity of this lateral dimension to river systems was recognised by the earliest agricultural societies who settled along the banks of the Nile, Tigris, Euphrates, Indus and Yangtze Rivers and exploited the rich soils that resulted from the seasonal deposition of silts and nutrients onto floodplains.

In many large floodplain systems in Africa, fish synchronise their reproduction with this period of increased productivity, with the adults migrating onto the inundated areas to lay eggs (Welcomme, 1985). In the Pongola River under natural flow conditions, for instance, gonads of many fish species ripen to coincide with peak flows between October and March when the fish migrate onto the floodplain to spawn

(Merron et al., 1993). Once the fish larvae hatch they continue to feed and grow in the rich pans of the floodplain until they are large enough to move into and withstand the higher velocities and increased predation levels of the main channel. At a smaller scale, wetland-floodplains in upper river reaches are also important for providing refuge for invertebrates and fish during floods, when flow forces in the main river would otherwise wash them downstream.

The lateral exchange of nutrients and carbon between river and floodplain and the shift from terrestrial to aquatic habitat that occurs with inundation of the floodplain is reversed as flood flows subside, leading to a phase of drying and a reverse shift towards a terrestrial system – hence the idea of an Aquatic-Terrestrial Transition Zone that shifts on a seasonal basis. The retreating flood pulse will contribute new sources of carbon and nutrients into the river channel as waters drain off the floodplain. The shape of the flood hydrograph, that is, the speed with which the floodplain is flooded, the length of the period of inundation and the frequency with which inundation occurs all influence the life history and behavioural responses of the animals and plants, and thus their adaptation to specific flood patterns. If the flooding is variable in its timing, for example, then this should provide an evolutionary force selecting for fish species that have a long potential breeding season and can wait for optimal conditions. If, on the other hand, the duration of flooding is highly variable then this would select for species with shorter life cycles, those that reach maturity quickly, or those that are in-channel rather than floodplain spawners.

The Berg River in the Western Cape has a floodplain and estuary of national and international importance. In this floodplain river, small by international standards, floods are short-lived and the annual hydrograph is seen as 'flashy'. Many floods may occur per year, or none at all, in contrast to tropical systems where massive flood pulses are seasonal events lasting many months each year. A map of the Berg River floodplain demonstrates the mosaic of vegetation and habitat types created by the dynamic interplay of land and water (Figure 2-8) outside the main channel of the Berg River. The mosaic results from inundation of the floodplain from the main channel, and the varied patterns of sediment deposition. The frequency with which inundation and sediment deposition occurs differs in different parts of the floodplain, giving rise to patches with different chemistries and different plant and animal communities. In addition, as an estuarine floodplain, the reach of tidal fluctuations up the estuary and laterally beyond the channel interacts with downstream river flows, further influencing water chemistry of the floodplains.

Hydrodynamic and digital terrain models are an important component of ecohydraulic studies of such areas. For the Berg River floodplain, a two-dimensional hydrodynamic model provided a time series of daily water levels over a three month period for a series of numbered points on the floodplain (Figure 2-8 and Figure 2-9). Some floodplain patches were perennially inundated, such as the pan at point 37, and then depth variation would be driven by flood events, as indicated in Figure 2-9. Other areas were dry for much of the year and inundated only occasionally when floodwaters pushed into back channels, such as point 36. For areas closer to the estuary mouth, such as point 78, tidal fluctuations were as important drivers of water levels as were river floods, and the interaction between tidal stage and flood size was demonstrated to be a critical aspect of the flooding regime. Figure 2-8 shows that at point 78, the magnitude of the tide rising and falling was responsible for regular depth variations. Depending on the tidal stage therefore, a flood routed through the estuary may either exaggerate the amplitude of depth variation, where a flood coincides with high tide (point A in Figure 2-9) or indeed could simply be absorbed by the floodplain, in the event of a low-tide coinciding with a flood (point B in Figure 2-9). These kinds of data are of enormous use to ecologists in studying the relationship between the natural hydrological regime and the plant or animal composition of different habitats within floodplains and/or in suggesting managed flows that should be maintained after upstream water-resource developments.

The seasonal rising and lowering of water levels along the channel margins is equally important for rivers, or parts of river systems without floodplains. In such rivers, seasonal fluctuations in water levels give rise to distinctive riparian zones: long belt-shaped areas along river banks that have alluvial soils, are regularly inundated during high flows and have geomorphological features and plant communities that are distinct from the adjacent land. In the riparian zone a lateral zonation of vegetation communities from wetted channel to the outer extreme of flooding is now commonly recognized (Boucher 2002), with different communities of riparian plants occurring at different heights above the water (Chapter 3). Riparian zones tend to be very narrow, sometime only one or two trees wide in headwater streams in incised channels and widening progressively downstream to as much as a kilometer or even more as valleys become wider and flood waters can more easily expand out of channels.

Riparian zones in low-order headwater streams have a profound effect on the physical characteristics of the river environment, such as temperature and light penetration, through shading, and they also form the primary source of energy – allochthonous material, in the form of leaf debris – for instream fauna. Fallen trees are also a structural component of these stream reaches, determining the extent to which organic matter is retained or transported to downstream reaches. Leaf packs, accumulations of leaves and organic matter that form in debris dams and on snags or hydraulic dead zones, provide both the major food resource and hydraulic shelter for a myriad of stream organisms.

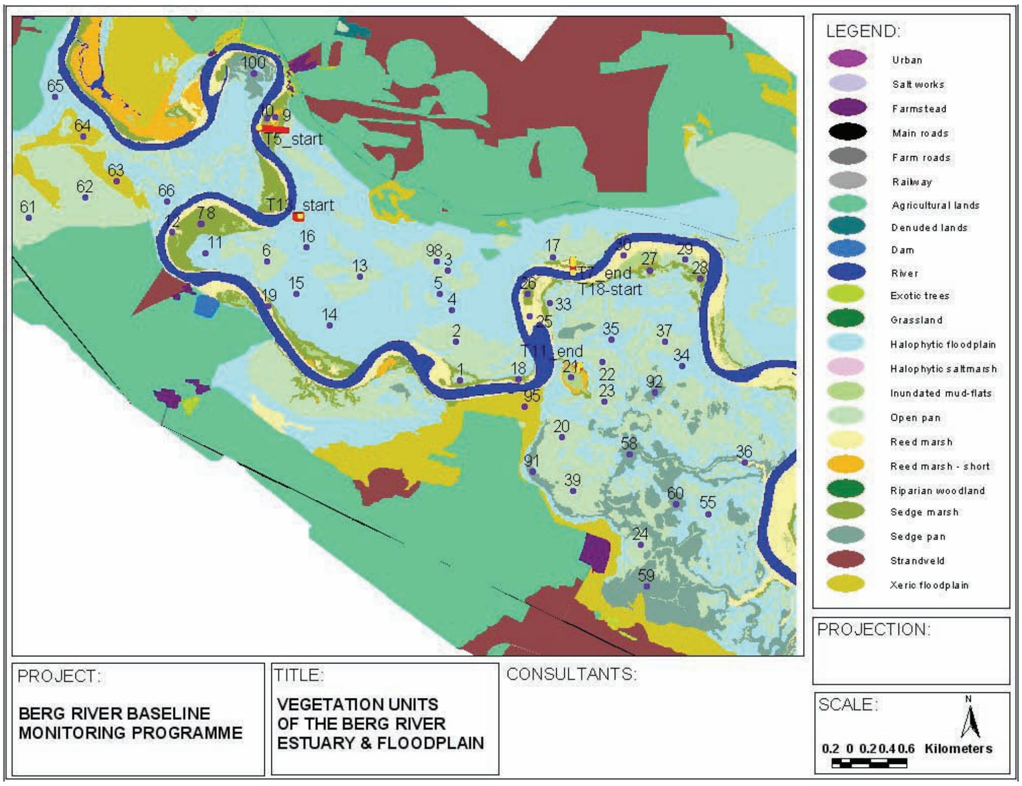

Figure 2-8 **Portion of the detailed mapping of floodplain vegetation units on the Berg River floodplain. Numbered points represent positions for which hydraulic time-series data were obtained using two-dimensional hydrodynamic modeling (Boucher and Jones, 2008)**

Downstream of forested headwaters, riparian zones gradually decrease in influence in terms of energy input as the river widens, because more light reaches the water allowing instream plant growth and the input of organic material to the river area is proportionately less than upstream. Their other ecosystem roles remain vital, however, as buffers between river and landscape, trappers of sediments, stabilizers of banks, areas of nutrient and water exchange with the channel and of flood attenuation and water storage. They are also key areas for surface-groundwater interactions, and where the water table or piezometric surface is above the river bed, then the river can be defined as an effluent river and discharge of groundwater into the river would be expected to sustain baseflow, as is typical of many rivers during lowflow periods. Similarly, in areas where the water table is lower than the river bed, the river may be seen as influent in character and water drains from it into the groundwater.

Rivers need not always be one or the other: during individual rainfall events, influent rivers may become effluent through groundwater influx into the river’s surface flow. Such fluxes are important for determining the nutrient budget of a stream. Differences between groundwater and surface flow, in terms of nutrient concentrations and of the abundance of organisms that fix or secrete nutrients, mean that fluxes of upwelling and down-welling provide temporally changing patches of nutrient availability and productivity within the stream.

2.3.4 The temporal dimension

The fourth dimension of rivers is a temporal one, with the most important temporal drivers being the flow, sediment, chemical and thermal regimes (Wohl *et al.*, 2007). Of these, none are considered more fundamental to driving ecosystem processes than the flow regime, which has variously been referred to as the ‘master’ (Poff *et al.*, 1997) or 'maestro' (Walker *et al.*, 1995) physical variable because of its ability to affect all others. This is considered further below.

The flow regime

The daily, seasonal and inter-annual variation in flow and its capacity to perform work on the channel is largely responsible for rivers being amongst the most variable and dynamic of ecosystems (Power *et al.*, 1988). To a large extent, the flow regime is responsible for the patterns in channel form as well as the fluctuations in biological communities, which respond both in terms of their composition (the kinds of species present), and structure (the proportions of different types of species). It is responsible for driving ecosystem processes such as nutrient cycling, and evolutionary processes such as a species’ morphological, behavioural and life history adaptations to flood or drought.

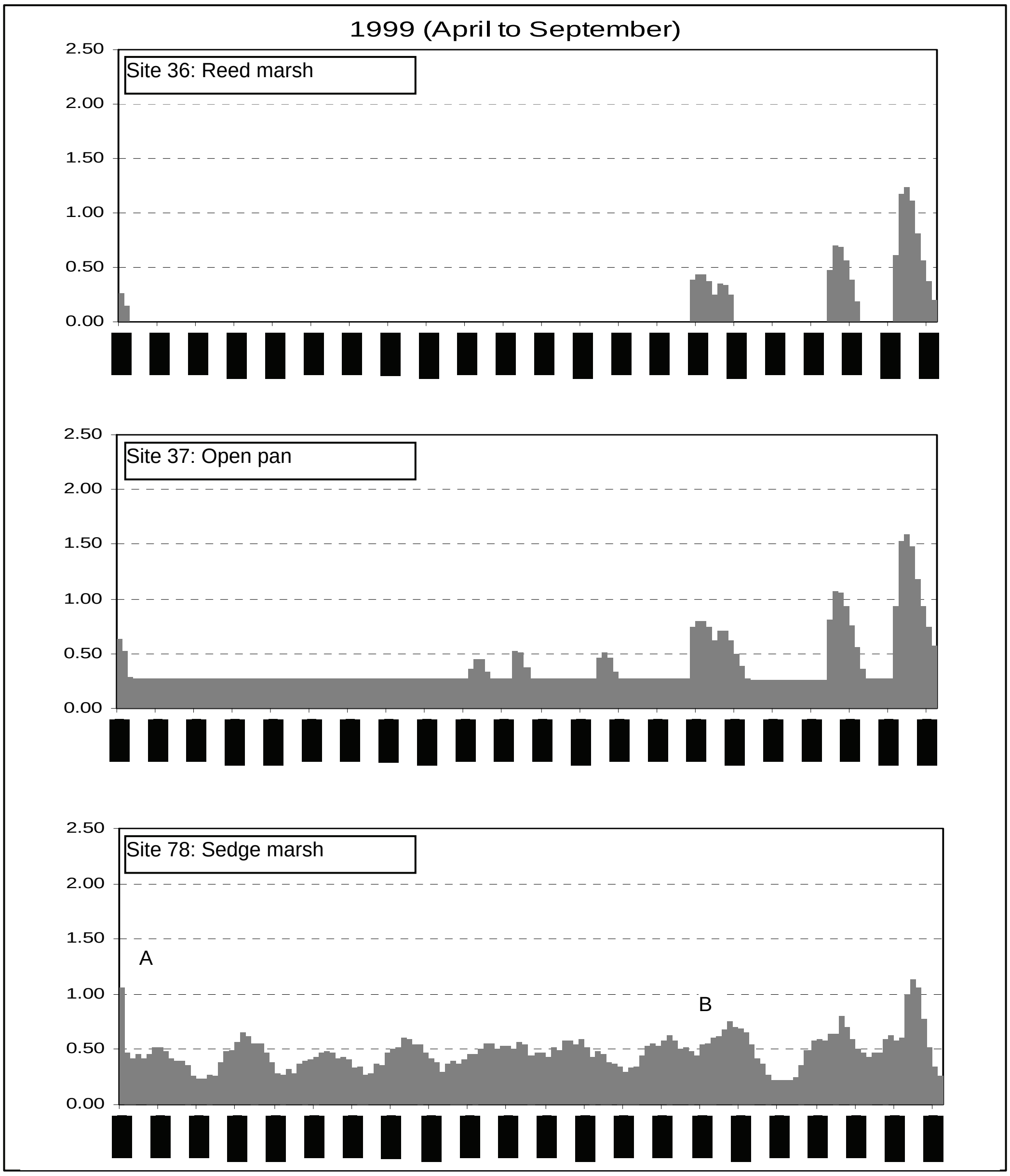

Figure 2-9 **Time series of daily water depth (m) at three points on the Berg River floodplain, corresponding to different habitat units shown in Figure 2.5 (Boucher and Jones, 2008)**

The Natural Flow-Regime Paradigm provides a framework for understanding the role that flow plays in shaping the adaptations of living organisms (Poff *et al.*, 1997; Lytle and Poff, 2004), reflecting it's annual, seasonal, daily and even hourly fluctuations. King and Tharme (1994), Poff *et al.* (1997) and King *et al.* (2003) proposed several of the following seven key parameters that need to be addressed when describing the flow regime:

Magnitude:	The quantity of water moving past a given location per unit time.
Frequency:	The number of flows of a given magnitude per unit time. The frequency of a flow of a particular magnitude can be classified as its return period, e.g. 1 in 5 years.
Predictability:	The certainty with which flows of a certain magnitude will return on an annual basis.

Timing:	The calendar dates in the year when flows of a certain magnitude (e.g. floods or droughts) occur. Key ecological processes are usually timed to coincide with their optimum flow periods in rivers.
Duration:	The length of time of flows of different magnitudes. This is particularly important for floodplain processes since it determines the period of inundation.
Rate of change:	The rate at which flows change in magnitude.
Variability:	The natural daily, seasonal and longer variability of flows.

The concept was developed further in an attempt to reduce vast data sets of measured or simulated hydrological data to manageable and ecologically relevant summary statistics. Flow categories were conceived, initially for South African rivers with flashy hydrographs, and designed to capture key aspects of the flow regime that riverine biotas are thought to react to (Table 2-4). Ten categories were recognised, namely dry and wet season low-flows, four categories of intra-annual floods and four categories of inter-annual floods.

Table 2-4 Categories of flows and major ecological functions that they are thought to fulfil in Western Cape rivers (after King *et al.*, 2003)

Flow category	Ecosystem Link
Dry season low flow	Maintain perenniality; trigger emergence
Wet season low flow	Maintain wet bank mosses and ferns
Intra-annual flood Class 1	Trigger fish spawning in late dry season; flush out poor-quality water
Intra-annual flood Class 2	Trigger fish spawning in early dry season
Intra-annual flood Class 3	Sort sediments, scour riffles, maintain habitat heterogeneity
Intra-annual flood Class 4	Sort sediments, maintain habitat heterogeneity, scour seedlings
Inter-annual flood up to 1:2 year	Maintain tree line
Inter-annual flood up to 1:5 year	Maintain tree-shrub zone; deposit sediments on banks
Inter-annual flood up to 1:10 year	Maintain macro-channel; re-set physical habitat
Inter-annual flood up to 1:20 year	Maintain macro-channel and outer zone of riparian vegetation

Later conceptual and practical development has encompassed rivers with non-flashy hydrographs and added a temporal dimension, through recognition of flow seasons (J. King, University of Cape Town, pers. comm.). In place of flow categories, ecologically-relevant flow seasons such as Dry Season, Transition Season 1, Flood Season, and Transition 2 may now be pre-chosen on ecological grounds and then hydrological rules written to identify the start and end of each from year to year, as well as other attributes such as type of flood season and minimum flows in the dry season. The resulting summary statistics are used to typify the natural and present-day flow regimes and variability of rivers as well as how these may change in any future management scenario.

Floods and the renewal of habitat quality

Interstitial spaces between bed particles are vital refugia for the small aquatic life of rivers and blockage of these spaces by fine sediments, making them inaccessible, has serious implications for their survival. Reduction in the amount and quality of interstitial spaces also has implications for water quality: an increase in fine sediments reduces gravel permeability and leads to lower dissolved oxygen levels in pore water (Chapman, 1988). The exchange between surface and groundwater via the stream bed, including thermal attenuation, decomposition of organic matter, and nutrient cycling also depends on the extent to which water can percolate into the hyporheos, which is in turn controlled by the extent of sediment deposition in interstitial spaces.

The degree to which fine sediments infiltrate or cover larger river-bed particles (Figure 2-10) is commonly referred to as embeddedness (Sylte and Fischenich, 2002). Measures of embeddedness indicate the availability of interstitial spaces and the permeability of the bed for small organisms such as invertebrates and fish eggs, water-quality constituents and organic matter, affecting invertebrate population densities and fish spawning success and recruitment.

Figure 2-10 Embedded (left) and scoured (right) river beds illustrating the availability of interstitial spaces among river cobbles and boulders

Both the deposition of fines and the scouring of interstitial spaces are natural processes in most rivers, occurring at seasonal or at irregular intervals depending on the flow regime and the timing of floods large enough to initiate this process. Both alteration of the flow regime and catchment management practices that increase the supply of fine sediments to the drainage network may alter the dynamics of sediment deposition and removal, with knock-on effects for biotic communities and nutrient dynamics. For example, an increase in the sedimentation of interstitial spaces may have the effect of lowering streambed roughness to the extent that floods no longer dislodge larger bed particles, thus reducing or preventing the sorting of sediments and renewal of habitat for stream organisms.

Periphyton (algae attached to rocks) blooms are a natural feature of many, even largely un-enriched rivers, associated with increases in temperature and light. In rocky, open-canopied rivers with clear water, periphyton is often the dominant food source for invertebrates, and thus an important ecosystem component. Its abundance may increase rapidly where invertebrate grazer densities are low because of regulation by floods and temperature, but if the abundances increase to become dense mats the quality of habitat for invertebrates and fish can be negatively impacted, even to the extent of certain habitats becoming inaccessible. An example has already been made of algal mats preventing fish passage (Section 2.3.1). Furthermore, seasonal shifts in the actual species composition of periphyton often mean that late summer algae are dominated by blue-greens that are unpalatable to many invertebrates. Floods are important means of controlling periphyton biomass and re-setting community composition (Biggs and Close, 1989), through:

- increased shear stress, because of higher near-bed velocities
- substratum instability, caused by the initiation of bedload movement
- abrasion by suspended solids.

Floods, low flows and nutrient spiralling

Nutrient spiralling along rivers is influenced both by the flow regime of the river and by movement of water into and out of groundwater through upwelling and down-welling. Nutrient sources for the river are created by the first phenomenon and nutrient sinks by the second. Spiralling may be more intense when surface flows are low, with almost closed loops sometimes forming when hydraulic conditions encourage increased retention within the stream bed.

A simple and elegant study by Dent and Grimm (1999) examined longitudinal changes in phosphate and nitrate concentrations at the points of strongest flow within the active channel. Immediately following seasonal floods, there was little difference in nutrient concentrations along the river, but conditions changed locally with time since flooding, with large differences in phosphate and nitrate levels over distances as small as 25 m river length. The spiralling of these nutrients was transformed into almost closed loops by low flow rates and the ensuing facilitation of high uptake rates by algae, leading to the development of nutrient-rich patches of algae. Seasonal or periodic increases in flow or in groundwater inflow would either provide pulses of nutrient-rich water to the water column, or, in the case of floods, reset these cycling loops through the scouring of accumulated algae and detritus from the stream bed and hyporheos.

The flow regime and temperature

Natural climatic cycles drive hourly, daily, seasonal, yearly and longer fluctuations in the hydrological, hydraulic, thermal and chemical attributes of the river, providing challenging conditions that riverine biotas must be able to cope with. By example, Western Cape foothill rivers support different invertebrate communities in summer and winter (King, 1981), and yet the summer communities may regularly have to face minimum temperatures that are almost as low as the winter ones as well as very high day-time temperatures (Figure 2-11). A large part of the temperature variability in rivers is the result of the influence of flow and hydraulics: spatial differences in hydraulics can magnify or ameliorate the seasonal temperature ranges with which the biota must contend. Water temperatures in backwaters, for example, where water flux is minimal, reach far higher daily levels than in the main channel, whilst deep pools often provide a temperature refuge for many fish.

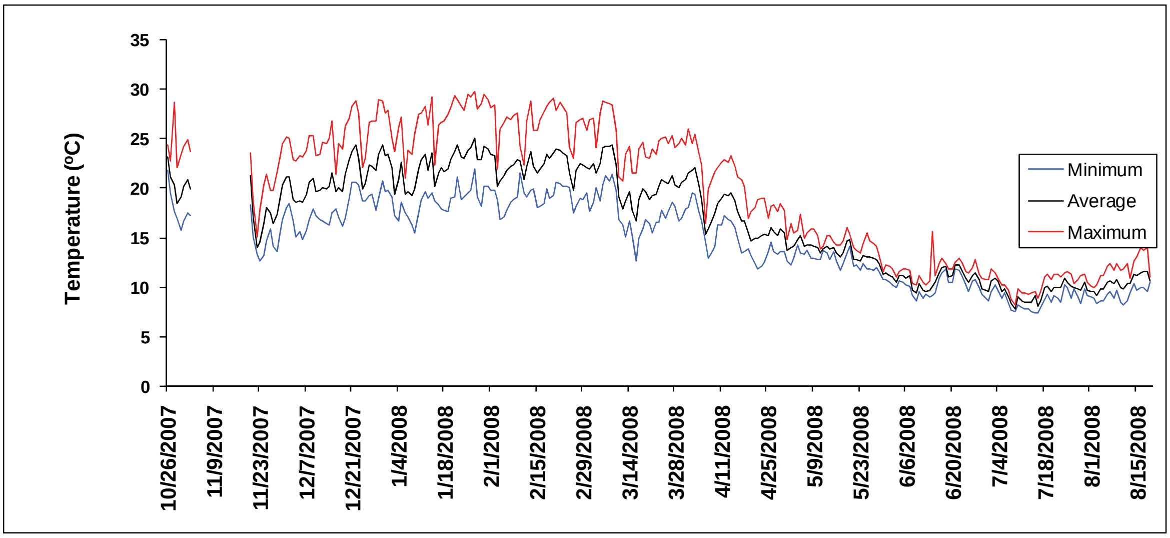

Figure 2-11 **Daily variability in temperatures in a single riffle in the Molenaars River, Western Cape, over an eight month period (data from Justine Ewart-Smith, University of Cape Town)**

Floods and droughts as a disturbance

River ecosystems can be affected by natural disturbances such as droughts and floods, as well as by man-made ones of a wide variety, all of which elicit responses from the biotas. Natural disturbance regimes have played a major role in the evolutionary adaptations of plant and animal species for life in or beside rivers – adaptations that are now built into their genes, dictating the extent and direction of their responses to both future natural and unnatural disturbances.

The natural disturbance regime of a river is thus considered one of the most fundamental determinants of which plant and animal communities the river will support, and is a major theme in river ecology. Disturbance can be thought of as an event of relatively limited duration, the magnitude of which may be sufficient to kill or displace organisms or populations, or to alter consumable resources and habitat structure (Lake, 2000). The ecological importance of disturbance is that through its effect on the inhabitants of a stream, it opens up new spaces that can be colonised, or alters resources used by individuals of the same or different species (Townsend, 1989).

Early definitions of natural disturbance of rivers by floods almost exclusively used one or other hydrological index, such as the 1:2 year return flood, with later attempts to capture this concept being through other means such as the flood flow categories in Table 2-4. Similarly, droughts have often been defined by a specific, often arbitrarily chosen, return period with no recognition of geographical differences.

This basis for defining disturbance does not recognize that a drought or flood of the same return-period in two different rivers may have substantially different hydraulic effects, depending on catchment geology, and channel and bed properties. The biological responses could therefore be very different. For this reason, disturbance in rivers should be measured and quantified simultaneously as a physical force, defined hydraulically, and as a biological response event, both being measured at the same scale. For example, if the physical force is measured in terms of increased shear stresses over patches of the stream bed, then biological responses should be measured also at the same patch scale.

Biological responses to flow disturbance are further discussed in Chapter 3, but in physical terms disturbance may be measured using the flood-driven movement of substratum particles (e.g. Lancaster and Hildrew, 1993; Death and Winterbourn, 1994; Townsend *et al*., 1997; Downes *et al*., 1998; Biggs *et al.*, 1999; Bond and Downes, 2000; Gjerløv *et al.*, 2003). The scale at which disturbance acts for invertebrates, and therefore should be measured, is not the stream reach level, but rather the more localised scale of individual stones or, in gravel-bed rivers, patches of scour or fill. This forms one of the major frontiers for ecohydraulic research.

In order for river communities to survive major disturbances such as floods and droughts, their members must be able to escape the worst effects of the disturbance. Many do this through the use of refugia such as deep pools, the hyporheos, marginal vegetation and floodplains: habitats that reduce the effects of disturbance or provide mechanisms for the persistence of biota in disturbed environments (Sedell *et al.*, 1990). At a local scale, benthic invertebrate assemblages generally recover from flood disturbance in time spans of less than one generation (King, 1981), suggesting that refugia are extensively used through either active or passive movement into them during floods. Recolonisation of the streambed by invertebrates after floods may occur simply by redistribution of individuals from refugia within any one stretch of river, or as imported individuals from upstream (Matthaei *et al*., 1999).

Instream flow refugia from floods are mostly localised areas where hydraulic forces acting on the substratum remain low even during a flood. Hydraulic dead zones may be seen as non-flowing areas of transient storage within the water column, such as in turbulent eddies, channel margins, wakes around larger bed elements, and reverse flows within pools and on bends (Lancaster, 2000). The availability of such hydraulic refugia will be dependent on channel heterogeneity and bed morphology, with roughness elements creating resistance to flow. Investigating this concept, Matthaei *et al*. (2003) recorded scour, fill and stable patches in a stream bed over the course of a flood, and these were associated with different levels of disturbance of the resident biota.

Hydraulic dead zones have been posited as a novel approach to examining the flow refugium potential of stream reaches. This is an interesting avenue for ecohydraulics research, as it classifies streams on how they are expected to affect population changes in the biota through flooding. For example, Lancaster and Hildrew (1993) identified different stream types (Figure 2-12) according to:

- the proportion of streambed occupied by hydraulic dead zones
- changes in the frequency distributions of shear stress with increasing discharge.

Type I streams are seen as more retentive and are characterised by a skewed unimodal distribution with a majority of low shear-stress spots at low flows, shifting to a bimodal distribution at higher flows. In this latter state, these streams have a greater proportion of areas with higher shear stress than during low flow conditions, but nevertheless retain a prevalence of areas with low shear stress, representing refugia that remain even at elevated flows.

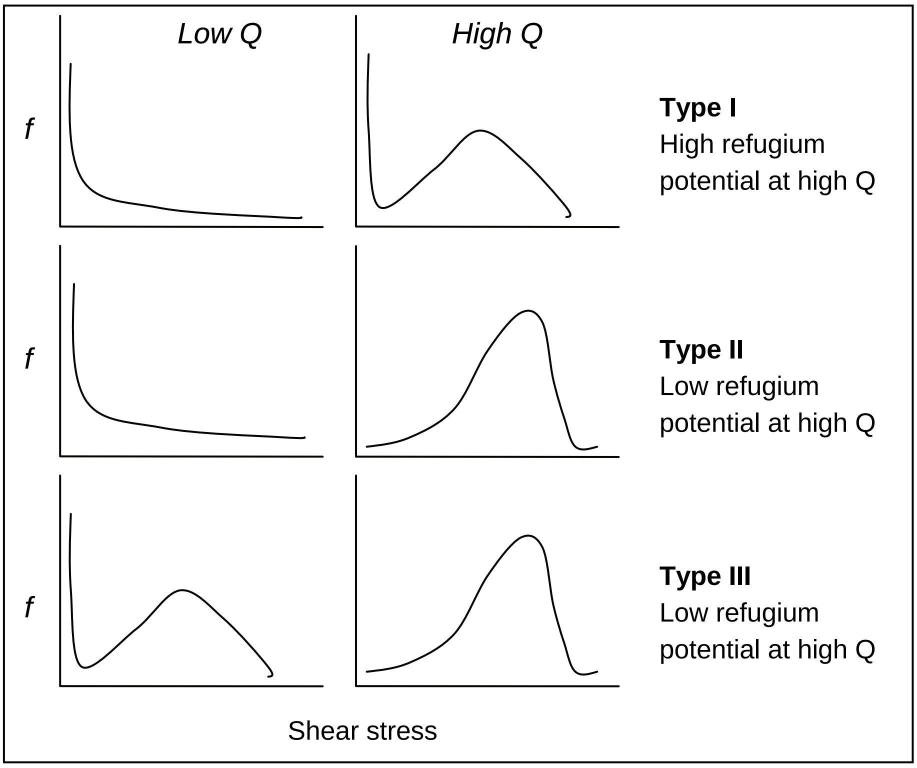

Figure 2-12 Characterisation of instream flow refugium potential in streams with different shear-stress distributions at low and high flows (after Lancaster and Hildrew, 1993). Q = discharge; *f* = frequency of occurrence

At the other end of the spectrum, Type III streams exhibit a bimodal distribution of shear stress at low flows, with high proportions of both low-stress and high-stress areas. They shift to a unimodal, bell shaped distribution at high flows with few or no areas of low shear stress. Type II streams are the most extreme in the change in their refugium characteristics associated with flow changes: these are similar under low flow conditions to Type I streams, with a majority of low shear stress areas, but are not retentive at all under high flows, where they shift to having mostly high shear stress across the stream bed, as with Type III streams.

They found that the proportion of streambed occupied by hydraulic dead zones was greatest with Type I streams, but this proportion was not consistently lower in the streams exhibiting lower refugium potential when based on shear stress distributions. These inconsistencies notwithstanding, such an approach may help to explain some of the variation in species assemblages between river catchments.

A second type of instream refugium during floods is large, stable, bed particles (Townsend *et al*., 1997; Francoeur *et al*., 1998) such as boulders. These particles may be subject to considerable hydraulic stress during a flood but for some organisms they could still be preferable to hydraulic dead zones where there could be other dangers such as increased encounters with predators. A local example is the net-winged midge, of the family Blephariceridae. The larvae of this family have streamlined bodies and powerful ventral suckers, and are only able to move slowly so cannot reposition themselves rapidly with impending floods as some other invertebrates can. Instead, their clinging ability allows them to remain on the surface of large clasts and simply to re-orientate during rising flood waters, to avoid the most powerful of the shear forces acting on the river bed.

2.4 Conclusion

Ecosystems are shaped by a number of environmental forces that impart to them their specific structure, species composition, and fluctuations in the abundances and distribution of organisms. These forces are ecological drivers – factors that exercise an overriding influence on the fitness and survival of individuals and populations (Poff and Ward, 1990). In rivers, the primary drivers are climate, geology and topography, manifested in the flow, sediment, chemical and thermal regimes of the river ecosystem (Wohl *et al.*, 2007). Of these, the most fundamental driver of ecosystem processes is the flow regime because of its ability to affect all others. The adaptations exhibited by living organisms for life in a temporally varying, flowing environment, are further addressed in Chapter 3.

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3. THE RIVER AS A LIVING SYSTEM

GR Ractliffe, BR Paxton and JM King

3.1 Introduction

Rivers are amongst the hardest-working of ecosystems, providing water for industrial, agricultural and domestic use, power generation and waste disposal, as well as a range of recreational opportunities. From an ecological standpoint, however, rivers are not just sources of and conduits for water, but are living systems and therefore part of the intricate fabric of life on the planet. The main channels, tributaries, riparian zones, wetlands, groundwater and floodplains of rivers jointly provide habitat for a multitude of vegetation types such as trees, sedges, reeds and herbs and animals such as insects, crustaceans, fish, amphibians, reptiles, birds and mammals, many being unique to a region. Rivers are ecosystems of great productivity and biodiversity, supporting some of the world's greatest fisheries and most iconic species, and a wealth of other species that underpin riverine ecosystem services that are vital for all of humanity. They provide vital resources for rural subsistence users, such as fish, firewood, construction materials, cooking herbs, medicines and are areas of immense social, cultural and aesthetic importance.

All of these ecological and social attributes of a river are threatened to a smaller or greater extent by water-resource and land-use developments within its catchment. River ecologists are becoming increasingly involved in advising on management and development issues pertaining to rivers, particularly regarding the ways the river ecosystem and its human users may be impacted upon by new water-resource developments or other management plans. Predictions of ecosystem change and social impact allow decision makers to make more informed decisions on river management and water-resource development, and thus move humanity forward toward a future of truly sustainable use of this vital natural resource. Such predictions need to be based on a recognition of the strong relationship between the fauna and flora of a river and their abiotic riverine environment, and thus their enormous vulnerability to human-induced changes to this environment with its knock-on effects on society. Creating such predictions is a complex task that must take into account all abiotic and biotic aspects of the river ecosystem, and is best done within an inter-disciplinary framework incorporating fluvial geomorphology, hydrology, hydraulics, water chemistry, and ecology at species, community and ecosystem level, in a manner that is reflective of the dynamic nature of river ecosystems and the patterns and processes that shape them (King and Brown, 2006; Dollar *et al.*, 2007).

An ecosystem may be defined as a community of different species, with the species dependent on each other and on their physical-chemical environment, and linked through flows of energy and materials (after Lawrence, 1996) (Box 3.1). The study of ecosystems, which is the domain of ecology, is concerned with how these abiotic factors and species interactions affect the abundance and distribution of organisms across the surface of the earth (Begon *et al.*, 1996). Ecosystems can be seen as hierarchically organised into a number of levels, from landscape units to individual organism, with each level contained within higher levels, but also functioning according to its own set of rules (Barrett *et al.*, 1997) (Box 3.1). The ecologist studies how each level operates as well as the ecosystem as a whole, in order predict the specific and wider outcomes of a change in any level of the hierarchy. The numerous potential interactions between and within levels of the ecosystem makes them exceedingly complex systems. Modifications to a single component – be it an abiotic or biotic one – can result in ripple effects that are difficult to predict and even more difficult to remediate. For example, reduced flows and increased grazing in the upper reaches of the Sabie catchment have resulted in increasing levels of sedimentation downstream in the Kruger National Park (Davies *et al.*, 1994) resulting in a transition from bedrock to alluvial conditions in the channel. This in turn has provided favourable conditions for the proliferation of *Phragmites* reedbeds (van Coller *et al.*, 1997). In a positive feedback mechanism that further exacerbates sedimentation, the reeds trap more sediment and increase evapotranspiration, ultimately leading to a loss of pool habitat for hippopotami, crocodiles and many other river-dependent species. The following sections outline some of the attributes of river ecosystems that should be taken into account when managing, and predicting ecosystem changes of, any river.

3.2 Life in running water

The physical, chemical and thermal properties of water as a medium for life provide a unique set of opportunities and constraints for living organisms. The behaviour of water as a fluid, its ability to dissolve other substances including oxygen, and its thermal and chemical properties have shaped the species that live in it. River-dwelling organisms have evolved strategies to breathe, feed, compete for resources, evade predation and reproduce in a comparatively dense, flowing medium that is continually changing. They need to be able to withstand periods of physical adversity, such as floods or droughts, cope with fluctuations in water chemistry associated with low-flow periods and maintain position in a preferred habitat in the face of a relentlessly flowing river. They have evolved to meet these challenges in a number of ways. The most obvious adaptations are to their:

- morphology or body shape, such as the presence of fins, gills, suckers, or claws that can grip the river bed
- physiology, such as being able to withstand drought or fluctuating temperatures
- behaviour, such as selecting specific river reaches or habitat conditions to live in, or developing rapid responses to environmental cues that improve their chances of survival during high or low flows
- life cycle strategies, such as using flow-regime cues to trigger egg laying or seed setting.

These are discussed further below.

Box 3.1

Ecosystem Definitions

Species: organisms that have morphological features in common and that are capable of interbreeding and producing fertile offspring

Population: interbreeding organisms of the same species inhabiting the same geographical area

Community: populations of different species inhabiting the same geographical area that are linked by mutually dependent interactions

Assemblage: similar to a community: organisms that occur together but where the mutually dependent interactions are less obvious or less developed. The term ‘community’ is applied in this document

Ecosystem: a community of organisms and its physical, chemical and thermal environment, with linked flows of energy and materials

Landscape: An area of land including physical features (landforms), living components (plants and animals) and human components (agricultural, industrial or domestic land-use patterns)

3.2.1 Morphological adaptations

Breathing mechanisms

One of the challenges faced by organisms living beneath the surface of the water is oxygen uptake. Oxygen is dissolved in water from the surrounding air, especially where turbulence in riffles and rapids causes the entrainment of air bubbles. Whereas fish have evolved gills to absorb oxygen, invertebrates have evolved a remarkable range of strategies including by diffusion through the body wall (e.g. blackfly larvae), by having external (e.g. mayfly and damselfly larvae) or internal gills (e.g. dragonfly larvae), by trapping air between unwettable hairs or under wing covers (e.g. riffle and diving beetles) or by breathing air directly from the surface using a siphon (e.g. mosquitoes and water scorpions). Amphibians and many groups of aquatic insects undergo profound developmental changes that enable them to make the transition from water breathing to air breathing during the course of their life history. Many flow-dependent groups, such as most mayfly families, rely on the flow of water to deliver oxygen to the surface of their gills and are sensitive to reductions in flow for this reason (Bäumer *et al*., 2000). Similarly, the eggs of many fish species survive because river flow delivers oxygen to and removes metabolites from their vicinity (Chapman, 1988).

Anchors and ballast…and when to let go

The forces of lift and drag acting on an organism in running water present a challenge to its ability to feed, metabolise, grow, reproduce and maintain its position in a zone of the river with suitable physical, chemical and thermal conditions. As a primary adaptation, most aquatic invertebrates in rivers are therefore bottom-living benthic organisms rather than free-floating planktonic forms that, by definition, would be swept away by river currents. The benthic invertebrates, or benthos, live on the river bed or in the interstices between its stones, many inhabiting the quiet boundary layer that forms around rocks in flowing water due to friction. Benthic invertebrates have evolved a wide range of morphological adaptations to maintain position in the river, including body streamlining, hooks, suckers, grapples, ballast, claws and friction pads that prevent them being washed away (Figure 3-1).

The current may, however, be used to advantage. Downstream drifting is undertaken by almost all benthic insect orders, mostly at night to limit the risk of predation, and provides a means of dispersing young and moving to new areas (Brittain and Eikeland, 1988; Flecker, 1992). The eggs of many freshwater fish species are buoyant and designed to drift downstream for up to ten days before settling on the riverbed where the young hatch (e.g. Humphries *et al.*, 1999).

Walking on water

Near to the surface water molecules bond closely, creating a tension at the surface. For very small organisms this presents challenges for mobility, but for larger organisms, it provides a unique opportunity. It is here that some invertebrates have evolved to exploit what is probably one of the most insubstantial niches on the planet – the narrow interface between the air and water surfaces produced by surface tension. Fine hairs on the ends of their limbs increase the area in contact with the water enabling them to move across the surface. This adaptation has evolved independently in three insect orders including the water boatman (Corixidae), water striders (Gerridae) and backswimmers (Pleidae). Collectively referred to as the *neuston*, this group is necessarily only found in ponds and lakes and the slow-moving backwater areas of river channels, because faster flows would break the surface tension or sweep them away.

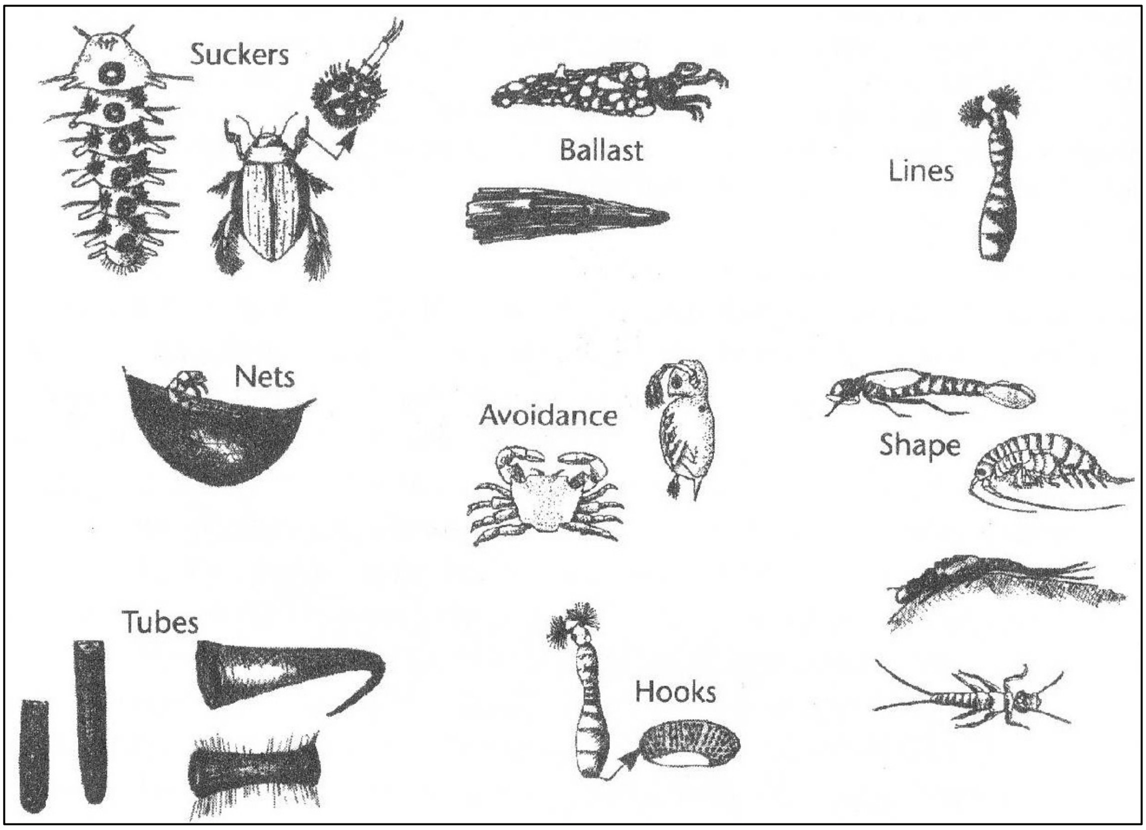

Figure 3-1 **A range of adaptations that river invertebrates have evolved to prevent themselves from being washed away in the current (Davies and Day, 1998)**

3.2.2 Physiological adaptations

Osmoregulation

The strong polarity between oxygen and hydrogen atoms in the water molecule gives water some of its unique properties as a fluid, such as its ability to dissolve other substances. This critical feature of water makes it suitable as a living medium since organisms must be able to absorb and expel salts and nutrients from their bodies during the processes involved in metabolism. Rivers derive their salts, such as sodium and chloride ions, from the landscape through which their waters flow. Both invertebrates and fish use osmoregulation to maintain specific concentrations of water and ions in their bodies. Unlike their counterparts in terrestrial and marine biomes, freshwater organisms must deal with an excess of water and a deficiency of salts because their body fluids are hypertonic in relation to the surrounding medium. Uptake of salts occurs through diet as well as active absorption through specialised cells, whereas the elimination of water occurs through excretion. This free interchange of materials across body surfaces, however, makes aquatic organisms particularly susceptible to pollutants. Frogs, for instance, are known as key indicators of environmental stress because they absorb pollutants readily through their skin (Roy, 2002). The worldwide decline in their numbers and diversity (Halliday, 1998) is a graphic indication of the decline in health of the world's rivers.

Temperature

Because enzymatic activity in cells is temperature dependent, this property governs many aspects of all life including the rate of growth and development of species, their distribution and the timing of critical life-history events (Magnuson *et al.*, 1979). Most riverine organisms are adapted to survive in a band of temperatures and are thus restricted in their geographical distribution. Many South African stoneflies (Plecoptera), for example, are relics of a time when temperatures on the sub-continent were much lower than at present. As a result, they are now restricted to cooler, forested mountain streams where temperatures correspond to those former conditions. Temperature is also one of the primary reasons that exotic trout species cannot survive in most South African rivers. Most local rivers exceed 25°C in summer, which is the upper limit for trout survival (Eaton *et al*., 1995; Myrick and Cech, 2000).

Higher temperatures mean greater primary productivity, enhanced availability of food and therefore faster growth (Bye, 1984; Cushing, 1990; Jobling, 1995). By example, the mayfly *Castanophlebia calida* was shown to grow larger and yet take less time to complete the aquatic phase of its life cycle with increasing distance downstream from the source – a phenomenon likely to be at least partially attributable to a downstream trend of increasing water temperatures (King, 1981). Many fish and invertebrates time their reproduction to coincide with higher temperatures, with temperature increases being primary seasonal cues that trigger the development of gonads and the onset of migrations and spawning in fish (Van der Kraak and Pankhurst, 1997).

3.2.3 Behavioural adaptations

Feeding

One of the advantages of life in rivers is that food is delivered by the continual downstream transport of organic material and organisms. Many invertebrates have adopted a 'sit and wait' strategy, much as sessile marine organisms on rocky shores have, employing many kinds of apparatus that enable them to trap material drifting past. A simple form of capture is filtration by rows of hairs, or setae, on the limbs or mouthparts, with the hairs then being wiped across the mouth to ingest the trapped particles. Blackfly larvae have more elaborate cephalic fans that they hold above their heads in the current to trap organic particles. Some caddisflies spin silk sheets between rocks, which trap particles and prey drifting downstream; they may be particularly abundant downstream of dams or lakes where the quiet waters have allowed the build-up of small planktonic organisms that are then swept down the river and into their nets.

Fish are powerful and efficient swimmers and are able, within limits, to counteract the forces acting to wash them downstream. But they modify their behaviour to balance energetic gains from food against the energy losses required to obtain it. When feeding off drifting invertebrates in rivers, for instance, Clanwilliam yellowfish (*Labeobarbus capensis*) minimise energy expenditure while maximising energy intake by selecting hydraulic cover in the form of velocity shears or behind cobbles and boulders in close proximity to areas of higher velocity that deliver their food. Thus, their ideal foraging sites tend to be areas of quiet waters close to fast-running riffles and rapids (Paxton 2008).

3.2.4 Life cycle strategies

In addition to the above adaptations, river organisms – indeed all living organisms – can be characterised by patterns of growth, reproduction and development that are as much a part of their suite of adaptive responses as the other traits. Most multi-cellular organisms undergo a sequence of physiological and morphological changes during the course of their lives that we refer to as their *life cycle*. Thus a typical aquatic insect, for instance, starts life as an egg that hatches at a time when environmental conditions are suitable, grows through several instars as an aquatic larva, metamorphoses into a pupa and finally emerges as an adult. Others short-circuit this process, hatching into tiny nymphs that are much the same shape as adults. These latter go through several instars of growth, shrugging off the old skin at each stage, with the final stage being the adult.

Each species has its own characteristic life cycle, with the timing, duration and nature of each life stage operating within specific boundaries. There is a maximum age and size that the species can reach, for instance, a maximum number of young that can be produced at any one time or over the course of a lifetime, and constraints on when and how often reproduction can occur. The organism's life cycle and these additional attributes are collectively referred to as a species' *life history* and the particular combination of attributes – whether it has a short or long life span, a small or large numbers of eggs, or reproduces seasonally or aseasonally – comprises a species' life-history *strategy* (Southwood, 1988). The effect of these life-history strategies on the population dynamics of organisms is illustrated with the following two examples.

Example 1: spreading the risk

Mayflies (the taxonomic order Ephemeroptera) are an abundant and diverse group of aquatic insects in running waters and their life cycles have much in common with other aquatic insect groups. The life cycle of the mayfly *Baetis harrisoni* begins when a gravid female deposits up to 4,500 small eggs into the river current. The eggs are distributed over the surface of the water where they drift for a brief period before settling on the river bed and starting development into nymphs. The hatched nymphs grow in the river from weeks to months, depending on the species, before reaching the final nymphal stage when they emerge from the water as winged non-feeding sub-imagos. These shed one last skin to transform into full adults, which appear simultaneously in large numbers, gather in mating swarms, copulate in mid-flight, lay eggs and die – all within hours or a few days of emergence from the water. The name Ephemeroptera reflects this ephemeral life of the adult.

Example 2: taking no chances

In contrast, the life cycle of the native Clanwilliam rock catfish *Austroglanis gilli* follows a very different pattern. As with the mayfly it begins its life cycle as an egg in the river bed. Instead of depositing its eggs indiscriminately, however, the female catfish selects a suitable location and then lays between 30 and 400 eggs, depending on the size of the fish, during the course of the reproductive season (Mthombeni *et al.*, 2008). Once they hatch, the young catfish develop through larval and juvenile stages to reach reproductive maturity after two years. They then contribute to the progeny of the next generation, through spawning in a single, discrete season each year for the next decade or so.

These two species illustrate some basic principles that have shaped our understanding of how life-history attributes affect the behaviour of populations. The mayfly is a risk-taker: its life-history strategy is to invest more energy and resources in the production of large numbers of small eggs and rely on the fact that at least some of them will survive to maturity. Because each individual mayfly attains sexual maturity within a year it is able to reproduce quickly and numbers build up rapidly, but there may be large inter-annual fluctuations in abundance as environmental conditions vary. Species with this life-history strategy are seen as opportunists (*r*-strategists)[1] – they are able to take advantage of favourable conditions to increase rapidly in abundance.

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[1] *r* is from ecological algebra denoting the growth rate of a population (MacArthur and Wilson, 1967)

The Clanwilliam rock catfish on the other hand is more conservative. It invests more energy and resources in producing fewer but larger eggs with large nutrient stores, and placing them in a favourable environment that increases the odds that a large proportion will survive. Many species that have adopted this strategy also invest considerable resources in parental care of the young. Because the rock catfish is relatively long-lived, takes several years to reach maturity and does not suffer high mortality rates, its population numbers tend to be fairly stable. Life-history theory predicts that these equilibrium species (*k*-strategists)[2] will remain at or near the carrying capacity of their environment, i.e. the maximum number of organisms the environment will support (MacArthur and Wilson, 1967).

From the life-history strategy a species adopts, it is possible to predict what type of environment it is likely to be found in and how it will respond to environmental change – natural or otherwise. Opportunistic species tend to prosper in habitats that are subject to frequent and unpredictable disturbances (Winemiller, 2005) such as may be encountered in arid-zone rivers (Walker *et al*., 1995). Their short life cycles enable them to rapidly build up numbers between disturbances when conditions are optimal (Humphries *et al.,* 2002) and they are usually the first to colonise areas after major floods or droughts (Zeug and Winemiller, 2007). Some may reach pest proportions if conditions are suitable over an extended period, as was reported for blackfly in the Vaal River when flows were manipulated (Chutter, 1968; de Moor, 1986).

Because equilibrium strategists are long-lived, they rely on the fact that they will live to reproduce in at least a few favourable seasons during the course of their lives. Because they cannot build up population numbers rapidly, they do not recover quickly after disturbances and therefore prosper in more predictable environments (MacArthur and Wilson, 1967).

There are, of course, variations on a theme. Even where species display risk-taking, there may be differences in the details of their strategies to survive in the face of disturbance, and in their successfulness in resisting adverse conditions. The population structure of two species of mayfly, *Baetis* sp. and *Demoreptus capensis*, at the start and end of a winter period of floods in the Berg River, Western Cape, are given in Figure 3-2. Both species recruit new young instars throughout the winter, as shown by the large number of small animals in the histograms. *D. capensis* is more successful at resisting flood disturbance, however, as shown by the bimodal distribution of animal sizes in July, indicating survival by larger, mature nymphs. *Baetis* sp. compensates for its lower survival rate during floods by high numbers of young instars. This may seem a maladaptive strategy, but in a mild winter without severe flooding the vast army of young *Baetis* recruits would be able to use a large algal and detritus resource whilst the other species is present at low densities. Such a life history adaptation, has its costs and its benefits in a variable environment.

Most organisms fall along a continuum between these two strategies (Jones, 1976) or combine features of both strategies (Pianka, 1970). Some invertebrate species have opted for an equilibrium strategy, just as some fish have opted for an opportunistic strategy. In all but the most extreme environments, such as ephemeral rivers where most organisms will be opportunists, a range of different strategies will be represented in the biological community of any particular river system. By altering the flow regime, humans can alter the community structure if the modified conditions favour one group over the other. In naturally variable rivers that become subject to more uniform flow regimes, equilibrium strategists are likely to be favoured, whereas if the flow regime becomes more variable and less predictable –

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[2] *k* is from ecological algebra denoting carrying capacity (MacArthur and Wilson, 1967)

downstream of a hydroelectric facility for instance – opportunistic strategists are likely to proliferate (Humphries *et al.*, 2002).

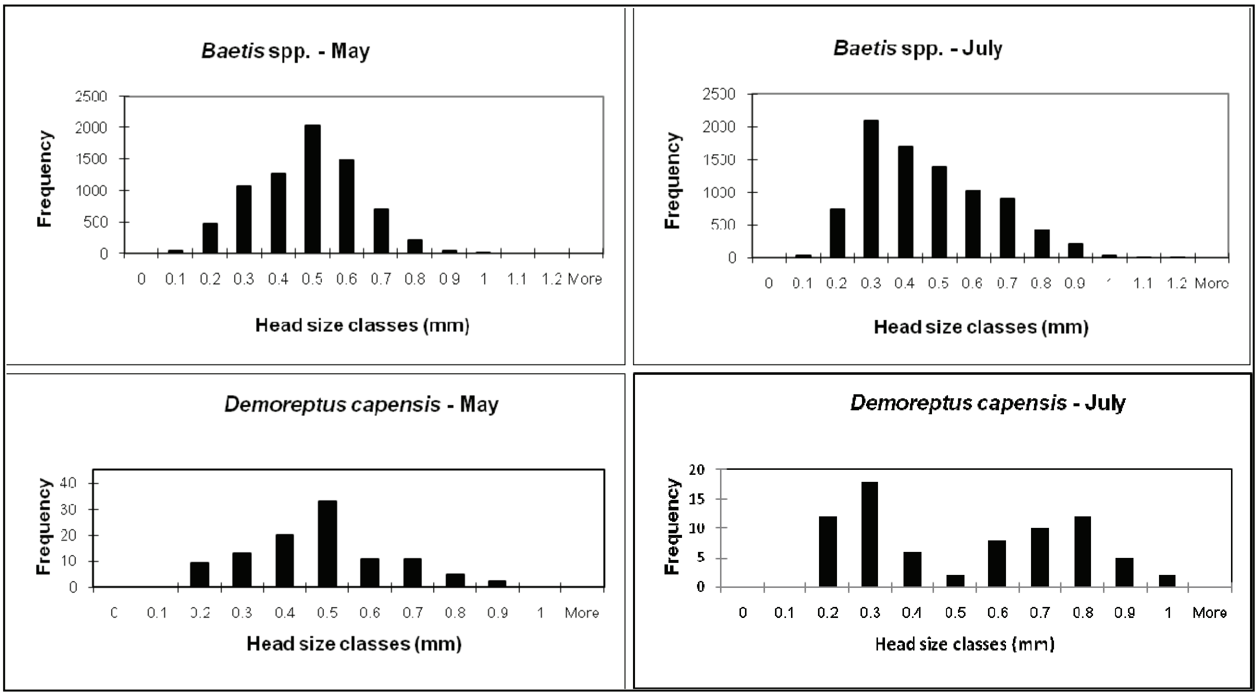

Figure 3-2 Population structure of *Baetis sp.* and *Demoreptus capensis* at the start (May) and end (July) of a winter period of floods in the Berg River. (Unpublished data, G. Ractliffe, Freshwater Research Unit, University of Cape Town).

3.3 Biological links to the flow regime

The links between a river's flow regime and its biota are many and varied. Two such links are outlined below to reflect some of the complexity of the relationship and the vulnerability of species and communities to flow change.

3.3.1 Flow categories and riverine plants

King (2003) reported that, although the evidence is still fairly sparse, links between ecosystem characteristics and specific flow categories (refer to Table 2-4) are emerging from South African research. For example, Boucher (2002) pointed out that in Western Cape rivers the maximum height reached by the 1:2 year inter-annual flood is closely linked with the lower edge of the woody Tree and Shrub community within the riparian belt (Figure 3-3). This plant community is one of several that inhabit different levels above water on river banks. Each community may be linked to a specific regime of inundation and drying:

- plants that live in permanent water would be in the aquatic zone
- mosses on the Lower Wet Bank would be under water or in the spray zone for much of the time
- sedges and reeds in the Upper Wet Bank would receive regular but less inundation
- The Tree and Shrub zone would be inundated rarely, but trees might be reliant on the occasional floods to bring sediment and nutrients to the bank and increase soil-moisture levels, enhancing conditions for seedling survival

- The Back Dynamic zone is the transitional area between the riparian zone and the surrounding terrestrial vegetation, subject to extremely infrequent flooding.

Further insights into inundation regimes can be gained from flow duration curves (FDC) (Figure 3-4). Hydrological data are used to construct the FDC, and also are analysed through programmes such as DRIFT-HYDRO (Brown *et al.*, 2005) to identify the approximate location on the FDC of the different flow categories. Surveying and hydraulic modeling produces a cross-section of the site with different discharge levels identified. Vegetation communities can be superimposed on the cross-section to ascertain the percentage of time that any one community is inundated. By example, the plant community within the wetted channel at bottom right is inundated for 70% of the time, and it is situated at this level in the riverscape because that is the condition it needs for survival. Analysis of the data used to construct the FDC will reveal the months in which that inundation occurs. Deviations from the natural timing, frequency and duration of inundation will elicit a response from that vegetation community – perhaps a shift over time to a higher or lower part of the bank; or shrinkage to a narrower zone, or disappearance from the river.

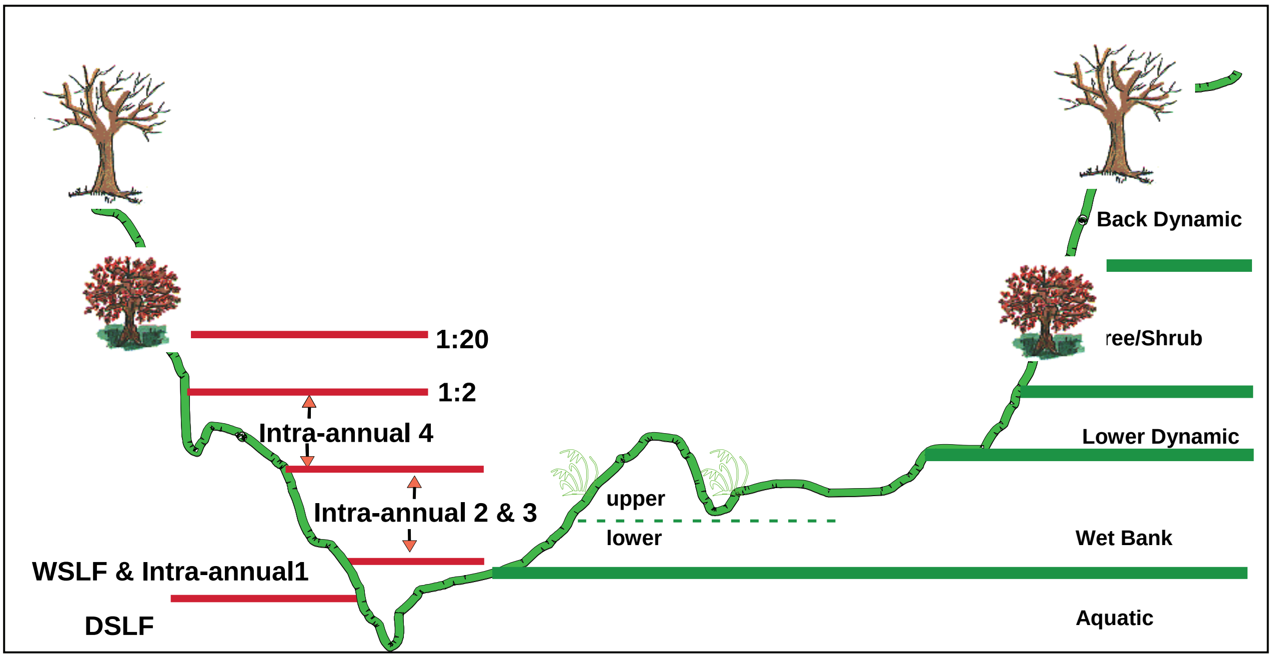

Figure 3-3 Lateral zonation of riparian vegetation in Western Cape rivers and possible links with flow categories (after Boucher, 2002). (Vegetation zones recognised by Boucher are shown on the right; Flow categories on the left. Flow categories as per Table 2-4)

Whatever the reaction from this and other plant communities to changes in the flow regime, there will be implications for the riverine animals using them and, ultimately for people dependent on any of these resources. Environmental Flow Assessments done in South Africa now facilitate a major link-up of disciplines to provide predictions of how possible future developments would impact on the river ecosystem and the people that depend on it: hydrologists simulate the potential modified flow regimes, hydraulicians model the ensuing hydraulic conditions, botanists predict how the vegetation communities could then change, zoologists predict the knock-on impacts on fish, invertebrates, water birds, herpetofauna and river-dependent mammals, and sociologists and resource-economists predict ultimate impacts on people that could be as varied as the decline or loss of wild medicine plants, firewood or fisheries and the loss of sites of cultural or religious importance (King and Brown, 2006).

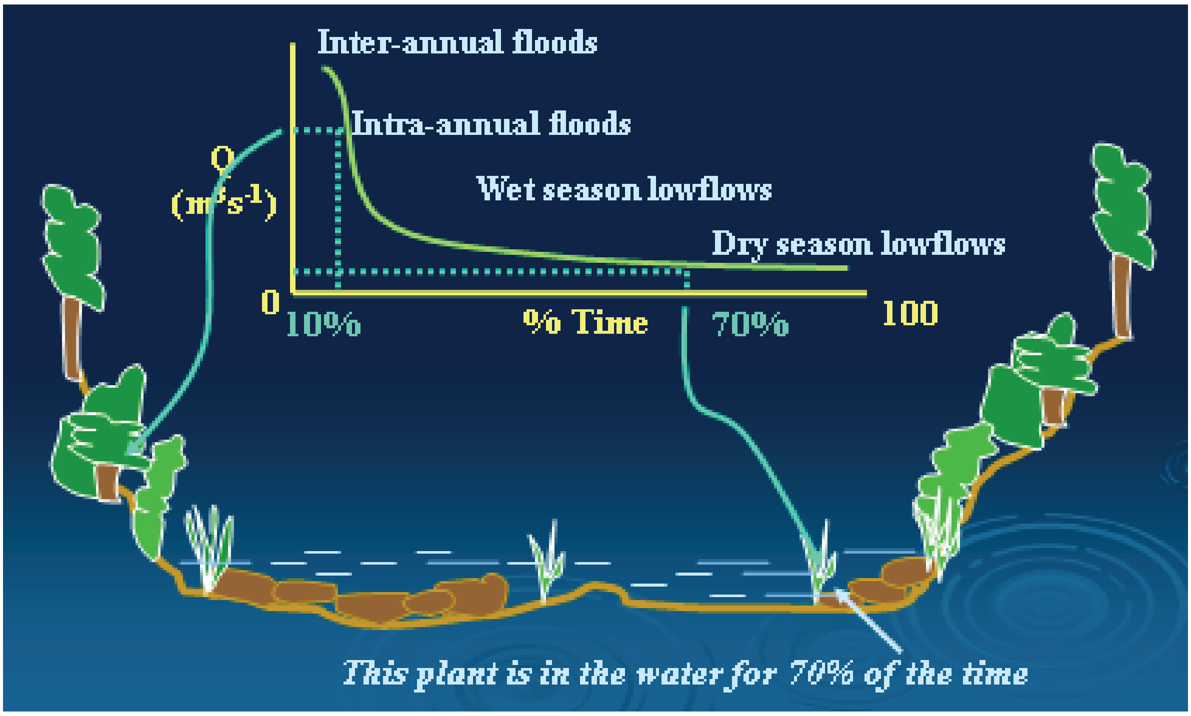

Figure 3-4 **Conceptual relationship between flow categories, flow percentiles, and zonation of riparian vegetation**

3.3.2 Invertebrates and floods

Almost all studies that have examined the importance of the magnitude of floods in controlling the numbers of riverine invertebrates point to the pivotal role played by the movement of coarse particles, or rock tumbling. Some species will be affected simply by an increase in the hydraulic force applied to a bed particle with rising floodwaters, before the onset of motion. For others, disturbance of the bed has to be profound and widespread before their numbers are reduced. The frequency of flows that provide different kinds of hydraulic forces will determine the relative abundances of species, often determining whether one species will be able to dominate and possibly exclude another.

An example of this is the study by McAuliffe (1984) on the patterns of abundance of two largely immobile stream invertebrates that compete for sites on river stones on which to construct their cases. One, the caddisfly *Leucotrichia*, builds sturdy cases and is able to use those vacated by previous generations. The other, *Paragyractis*, builds flimsier cases, and newly hatched individuals have to build their own cases. *Leucotrichia* thus has the considerable advantage of using older cases, and so becomes competitively dominant, excluding *Paragyractis* and others over time in the absence of rock-tumbling disturbance. In streams with a combination of overturned and undisturbed stones, however, both species coexist, because the more easily constructed cases of *Paragyractis* offer a competitive advantage when the bare substratum of newly-tumbled stones are colonised.

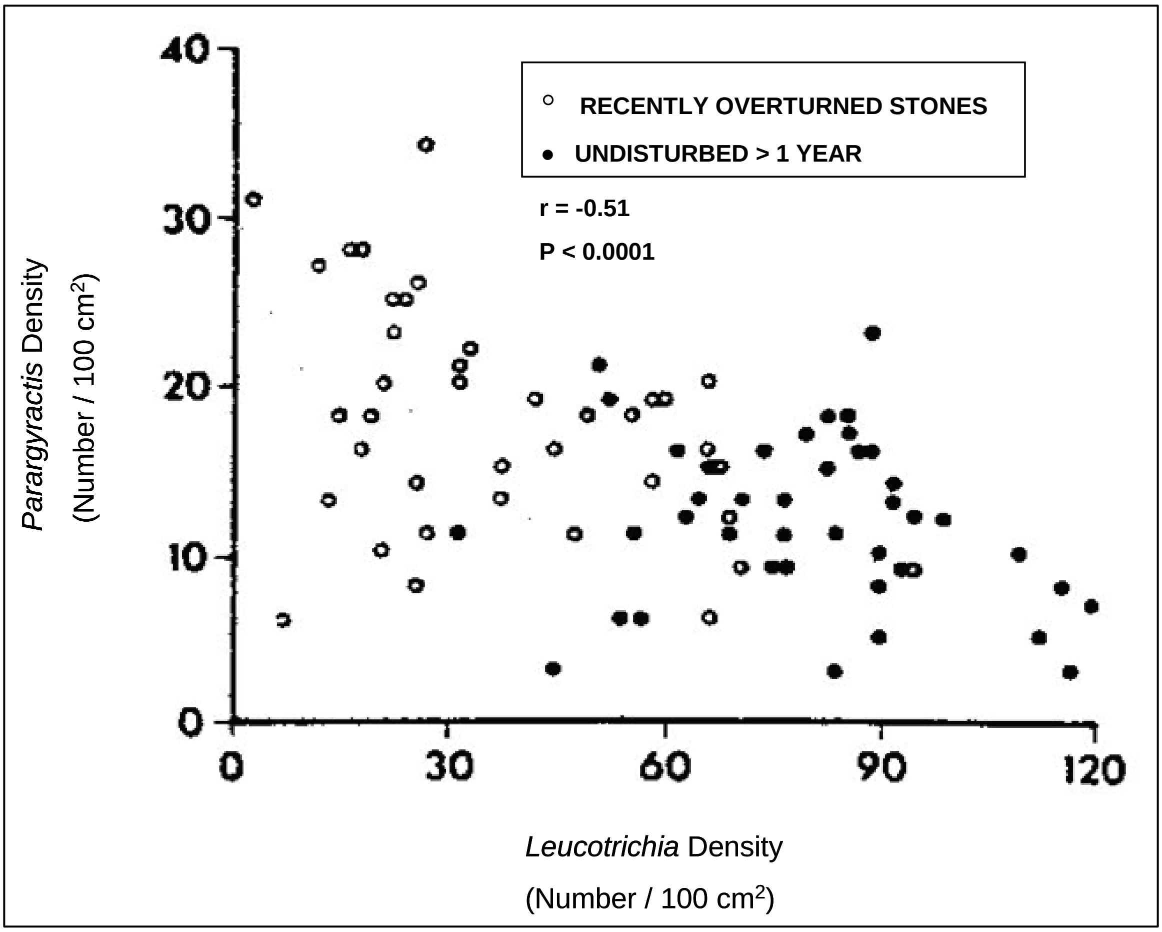

Figure 3-5 Negative correlation between *Leucotrichia* and *Paragyractis* densities on disturbed and undisturbed stones (McAuliffe 1984)

3.4 Stream communities – revisiting disturbance

The ecological concept of disturbance as a powerful sculptor of life in rivers was introduced in Section 2.3.4. This concept is re-visited to further explore its role in shaping the nature and functioning of riverine plant and animal communities.

Variability is essential for diversity. Environmental variability, both spatial and temporal, and of a physical, chemical and thermal nature, is a key factor in the maintenance of high levels of biological diversity in any ecosystem. Without it, an ecosystem becomes dominated by a few species that are best adapted to the uniform conditions, some exploiting the situation to reach pest proportions such as nuisance species in monoculture croplands. Even major disturbance events such as floods, although they may be catastrophic for some species in the short term, re-set the ecosystem by eradicating pockets of vegetation, scouring rocks clean, flushing out poor-quality water and washing some organisms away, thereby opening up gaps to allow less competitive species to re-establish themselves. Disturbances that are too severe or frequent may, however, result in a loss of diversity. But what then constitutes a natural level of disturbance? The answer is that there is not one natural or ideal disturbance regime suited to maintaining the natural characteristics and functioning of all river ecosystems.

The Intermediate Disturbance Hypothesis (Connell, 1978) proposes that the highest levels of diversity are maintained at intermediate levels of disturbance. At a high level of disturbance, only those species that are able to recolonise disturbed areas quickly will be present in the community. At a very low level of disturbance, biological interactions become increasingly important and those species that are good at out-competing others will dominate. Intermediate levels of disturbance allow for the coexistence of species that are good colonisers but poor competitors with species that are good competitors but poor colonizers (Figure 3-6). High levels of diversity are thus not necessarily the natural state for many ecosystems. Instead, the diversity characteristics – and the suite of species comprising the biological communities – in different rivers vary widely and are related to their natural disturbance regime.

If disturbances such as floods and droughts are relatively predictable then specific life-history adaptations should evolve to cope with them (Lytle and Poff, 2004). These may include, for instance, metamorphosis to a life stage that can withstand flood forces, with this being timed to coincide with the average onset of the flood season (Lytle, 2002). Life cycles may also be geared to maximise growth and reproduction during stable periods of quieter flow (Gasith and Resh, 1999).

Such adaptations have no value in rivers where floods and droughts are frequent and unpredictable. There, adaptations such as asynchronous hatching of portions of eggs over an extended time may be more useful (Huryn and Wallace, 2000), as would short life cycles that allow a quick response to favourable conditions (Chapter 2).

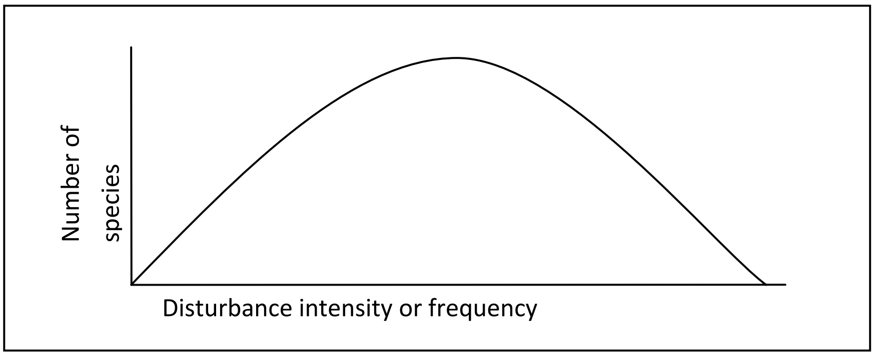

Figure 3-6 Connell's (1978) Intermediate Disturbance Hypothesis showing the relationship between species diversity and disturbance intensity or frequency

Viewed over large spatial and temporal scales, rivers should thus come to support the communities of species dictated by the habitat template they offer. Poff and Ward (1989) used the combination of flood predictability and flood frequency to develop a conceptual habitat template, and argued that the position of a river in terms of these two variables would allow predictions about the characteristics of its biota (Figure 3-7). The degree of intermittency of flow is the primary variable in the classification. For streams with low intermittency and for perennial streams, flood frequency determines the next level of the classification. For perennial streams, flood predictability provides a further axis in the classification. Each of the boxes in Figure 3-7 represents a different kind of riverine community, from those that are dominated by hardy pioneering species with high mobility, and where the community structure is determined by chance colonisation from a regional species pool (harsh intermittent), to those with highly predictable and stable communities, where biotic interactions such as competition determine the level of biodiversity (perennial, low disturbance).

Any physical or biological change to an ecosystem outside of the kinds of natural conditions shown in Figure 3-7 will disrupt relationships between species, probably reduce biological diversity and potentially cause community shifts characterised by loss of sensitive species and proliferation of robust species – many of which may have the potential to become pests.

Where change to the physical habitat in a river has been combined with the introduction of an invasive species, the effect on biological diversity is sometimes disastrous and irreversible. In the Olifants/Doring Rivers in the Western Cape, invasive largemouth bass *Micropterus salmoides*, smallmouth bass *Micropterus dolomieu* and Bluegill sunfish *Lepomis macrohirus* spread throughout the system following their introduction to the river system in the 1930s. Their impact on the local fish species has been devastating throughout the system, but nowhere more so than downstream of Bulshoek Barrage on the Olifants River where the combination of modified flow conditions and invasive fish species has destroyed habitat for the indigenous species and exposed them to predation they have not evolved to cope with. The result has been that the aliens have completely replaced the indigenous fish community in these reaches (Paxton *et al.*, 2002). Investigating the various hydraulic and other conditions that the alien and native fish species need, and manipulating them in favour of the native species, would provide one avenue for potentially reversing some of this impact (Gore *et al.*, 1991).

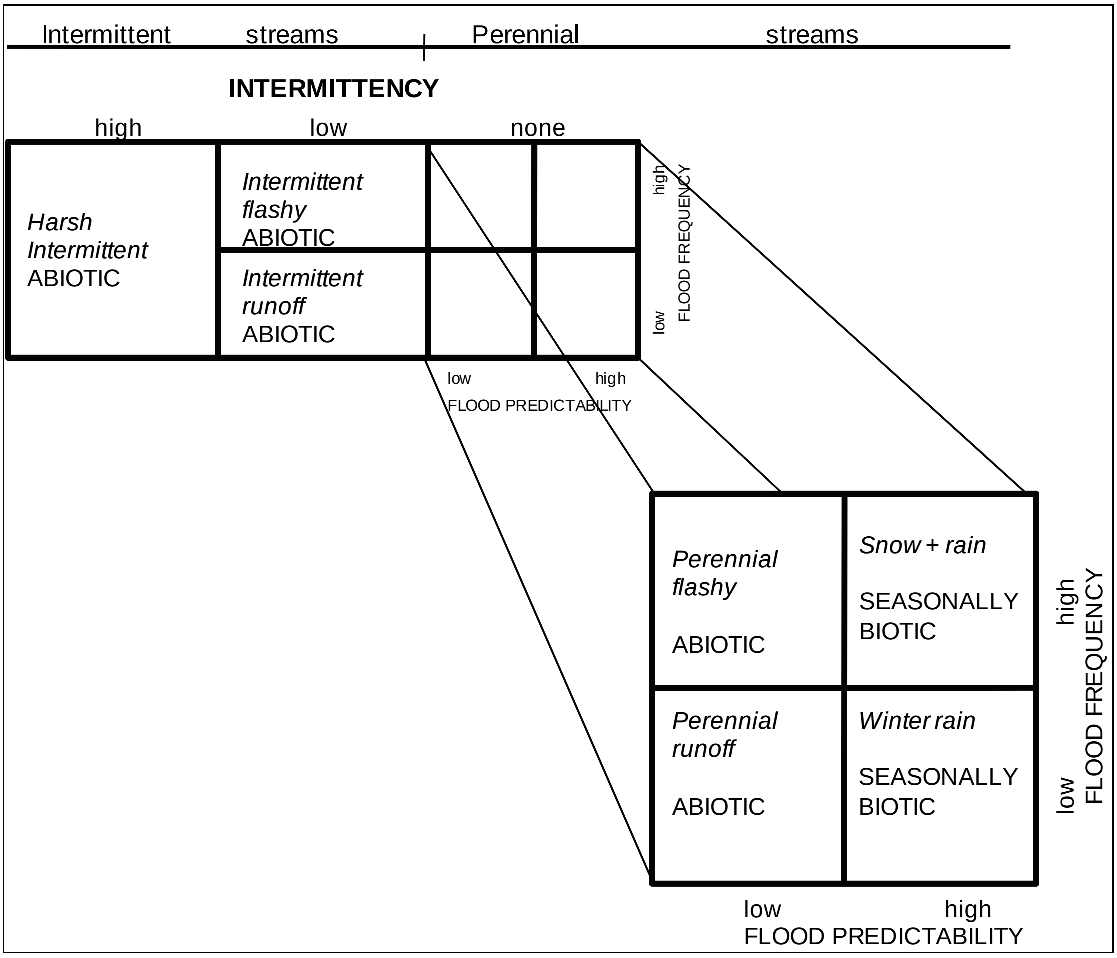

Figure 3-7 Conceptual model of stream classification based on characteristics of the flow regime (Poff and Ward, 1989)

The interactions and problems outlined above are some of the challenges of ecosystem management, where the goal is not only to conserve individual species, but also to preserve the diversity of species within the community as well as their habitats. In this way the functional links between organisms within a population, and populations within in a community, are maintained. The ability of a biological community to withstand change (its resistance) and to return to some former state after it has been disturbed (its resilience) depends on this diversity (Begon *et al*., 1996), and humanity's dependence on river ecosystems, whether or not acknowledged, relies on this ability.

3.5 Conclusion

Chapters 2 and 3 have provided a broad introduction to river landscapes, river habitats and river ecosystem functioning. They have shown that river habitats can be hierarchically organised into a mosaic of patches that can be defined at a range of scales from the catchment to the microhabitat or hydraulic biotope. They have outlined how the heterogeneity of river habitats and their dynamic properties play a major role in structuring river communities and therefore that the nature of these communities can be predicted, to some extent, from the type of habitat and its location in the broader river environment. Also, they have highlighted the fundamental role that river flow, and the flow regime, plays in both the physical structuring of river landscapes and the structure and interactions of biological communities.

The next chapter focuses on the hydraulic aspect of habitat over a range of scales and how it can be measured.

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4. DESCRIBING HYDRAULIC HABITAT

BR Paxton, GR Ractliffe, JM King and JDS Cullis

4.1 Introduction

Accepting the complexity of river ecosystem (Chapters 2 and 3) it follows that the continued presence of a riverine species or community can be compromised by a change in any one of many physical, chemical or biological components of its environment (Heggenes, 1996; Hardy, 1998). One of these physical components is the hydraulic nature of the habitat, and a key challenge to understanding why riverine species live where they do is to define this aspect of habitat. Once there is understanding of the hydraulic conditions that are optimal for different species or communities, it is possible through hydraulic modeling to predict how hydraulic conditions in the river could change with land-use or other relevant changes and thus how the habitat of the species/community could be affected. Fish species that need clean cobble beds with fast turbulent flow for spawning, for instance, could be expected to decline in numbers if flow was consistently slower and the cobble beds became smothered with fine sediments, and river scientists need to be able to describe and predict both of those conditions.

To make predictions of how changing hydraulic conditions could affect the river ecosystem, it is crucial to develop a database of information on the optimal hydraulic habitat for a range of key riverine species. The primary objective of this chapter is to detail some of the ways that data on hydraulic habitat have been collected, analysed and interpreted for rivers in South Africa, in order to alert practitioners to some of the key issues. The focus is on vegetation, fish and invertebrate studies, but the same general approaches to data analysis could apply to other parts of the riverine ecosystem.

The layout of this chapter reflects indirect and direct aspects of hydraulic habitat. Flows that indirectly affect species through sculpturing the morphology of river and thus their physical habitat are dealt with in Section 4.2. Those that directly affect species are dealt with in Section 4.3 (vegetation), and Section 4.4 (fish and invertebrates).

4.2 Flows and channel morphology

4.2.1 River channels

Flowing river water, with its load of sediments, endlessly works and re-works the river channel and bed, forming, maintaining and eroding channel features such as banks, bars, pools, riffles, secondary channels and islands. The hydraulic conditions created as a river flows along its course result in recognisable patterns of hydraulic features, such as the step-pool formations of mountain headwaters and the riffle-run sequences of foothill rivers (Table 2.2), each endlessly repeated through its respective river zone. Floods scour out new plants encroaching into channels, maintaining the channel’s width and its ability to convey flood water. Different-size flows are thought to move and sort alluvial deposits on the riverbed in different ways, providing discrete patches of particles from sand to boulder, which together offer a mosaic of places where different organisms can survive and so enhance biodiversity (Table 2.4).

This dynamic geomorphological world and its overlay of water defines the conditions in which riverine species must exist, and their various strategies for survival reflect this (Section 3.2). By example, deep pools and meander bends provide resting areas for adult fish; sandbars, slackwaters and side channels provide hydraulic and predation cover for juvenile fish; and cobble bars free of fines support diverse invertebrate communities. Changing the flow and sediment regimes that have shaped a river channel alters the quantity and quality of habitat for river organisms (Beck and Basson, 2003), and may threaten the ecological integrity of the river ecosystem itself. In South Africa and Australia (Brizga, 1998), flows for maintaining important features of river channel morphology have variously been referred to as *channel maintenance* or *flushing* flows, with the latter sometimes simply referring to flows of sufficient magnitude to flush fines from cobble bars. In this chapter the term *channel maintenance* is used since it addresses the full spectrum of channel features and the flows responsible for their formation and maintenance.

The formation of both small-scale (e.g. sand waves) and large-scale (e.g. meander bends) features of the river channel begins with the process of entrainment (erosion), transport and deposition of sediment by moving water. Whether or not a particle of any given size will be entrained, transported or deposited can be predicted from equations describing critical velocities, critical shear stresses or stream power (refer to Part III) (Gordon *et al.*, 1992; Jonker *et al*., 2001; Armitage and McGahey, 2003). These critical stages indicate flows that will move or deposit a sandbar, scour a pool or flush fines from cobble beds. Different flows shape different channel features, with more mobile features such as sandbars shaped by lower flows with shorter return periods, while larger, rarer events such as the 1:2-year flood, shape larger-scale features such as the active channel width (Dollar and Rowntree, 2003).

Understanding the relationship between a channel feature and flow, however, requires more than just instantaneous measures of velocity or shear stress; it also requires an understanding of the balance between variables such as discharge, sediment size and load and river slope, and how these interact through time (Brandt, 2000). Concepts surrounding the role of flow in shaping river channels have focused on the notion of a single or a range of channel-forming or dominant discharges (Inglis, 1941), i.e. discharges that are both frequent and sufficiently competent to affect major channel features (Knighton, 1984; Gordon *et al*., 1992; Brandt, 2000), and which implicitly encompass the above variables.

Channel-forming discharges have sometimes been equated with bankfull discharge (Brandt, 2000). The bankfull discharge for any river is that which fills the river channel without overtopping the banks, and is usually defined on the basis of morphometric variables such as floodplain elevation (Dollar and Rowntree, 2003) (refer to Chapter 8). Such a discharge is thought to be a moderate flood with a return frequency of about 1-2 years, rather than a larger flood that may be more competent to sculpture the channel but have a longer recurrence period (Wolman and Miller, 1960). The importance of a bankfull discharge for shaping channel features, as well as its recurrence period, differs from system to system. Heritage *et al.* (2001), for example, could not identify bankfull discharge on the Sabie River, since flows required to overtop the banks of the macro-channel exceeded those in the 62 year record. They did, however, show that marginal and mid-channel bar features of perennially flowing channels were inundated by flows with 1–1.5 year return periods. They suggested that the relationship between river flow and channel morphology may be more complex than thought, and that using the concept of bankfull discharge may be problematic in systems exposed to relatively recent climatic changes or tectonic events.

Identifying the flows responsible for channel maintenance requires a combination of expert judgment and examination of major breaks in the cross-sectional channel shape, floodplain height, vegetation zones and flow frequency (Gordon *et al*., 1992; Brizga, 1998). The specific approaches are beyond the scope of this report, and more comprehensive discussions of the topic in a South African context can be found in: Birkhead *et al.* (2000); Jonker *et al.* (2001); Armitage and McGahey (2003); Beck and Basson (2003); Dollar and Rowntree (2003) and Rowntree and Du Plessis (2003).

4.2.2 River floodplains

Rivers consist not only of the network of channels but also those parts beyond the active channels that are inundated when flows overtop the banks. Recurrent advances and retreats of water, with their accompanying sediment loads, dictate the extent and nature of a river's floodplain (Gordon *et al.*, 1992) (Box 4.1). Research on the relationship between river flow and floodplain processes in South Africa has focused mainly on the vegetation (Kleynhans *et al.*, 2007) or fish (Merron *et al.*, 1993). Those that have examined the formation of floodplains have done so from a geological rather than a hydrological perspective. The presence or absence of floodplain features along a river channel depends on the complex interactions of catchment geology, physiography, hydrology and climate. Many features of river channels in South Africa – including floodplains – are strongly influenced by the underlying geology. Tooth *et al*. (2002), for example, examined the effect of geological controls on the shape of the river channel and the presence of floodplain features on the Klip River, South Africa (Figure 4-1).

They found that the resistant dolerites downstream controlled vertical erosion rates in the upstream reaches. Overlying alluvial deposits in the upstream floodplain areas are shaped by processes acting over decadal and millennial timescales giving rise to the wide range of habitats such as oxbow lakes, and seasonally and permanently flooded backwaters typical of floodplains. There exists considerable scope for examining the role flow plays in creating and maintaining river floodplains.

Figure 4-1 Typical floodplain features on the Klip River: oxbow lakes and seasonally and permanently saturated backwaters (Tooth *et al.*, 2001).

4.3 Flows and aquatic, riparian and floodplain vegetation

In all but the most confined river valleys, communities of aquatic, marginal and riparian vegetation form an important feature of the active- and macro-channels, floodplains and other associated wetlands. Plant species differ in their needs in terms of soil moisture, soil texture and soil chemistry, as well as in their ability to withstand inundation and scouring floods (Malanson, 1993; Kleynhans *et al.*, 2007). Intimate links form with the pattern of flow in the river, dictating the vertical elevation above and horizontal distance away from permanent water of different communities of vegetation (Coetzee and Rogers, 1991; Higgins *et al*., 1996; Reinecke *et al.*, 2007).

The relationships between flow and vegetation communities in South African rivers have emerged from research programmes and consultancy reports over the past decade (e.g. Boucher, 1998; Boucher, 2001; King *et al.*, 2003; Birkhead *et al.*, 2005; Reinecke *et al.*, 2007). Zones of different kinds of vegetation communities from below the permanent water to the top of the bank have been described and, using hydraulic and hydrological modeling techniques, linked to different levels and frequencies of inundation (Table 4-1).

Reinecke *et al.* (2007) used a Classification and Regression Tree (CART: Brieman *et al.*, 1984) to identify four communities of riparian vegetation and their indicator species across 18 reference sites in the Western Cape (Table 4-2). Reinecke *et al.*'s groupings most likely match with those of Boucher (Table 4-1) as shown in Table 4-3; they did not report on the aquatic community.

Van Coller *et al.* (2000) also showed that riparian vegetation assemblages along the Sabie River, Mpumalanga, were associated with elevation above and distance from the river channel. The association with flooding frequency, however, was complicated by additional factors such as soil, substratum and nutrient conditions that also change with elevation. Thus, they caution against interpreting riparian zonation purely on the basis of river discharge. They suggest that, in addition to vertical and lateral gradients along the river channel, patchiness and the hierarchical structure in river geomorphology plays a key role in structuring riparian assemblages.

The study of floodplain vegetation requires an understanding of the timing, depth and duration of flooding and the extent of inundation. For instance wild rice growing on the Nylsvlei floodplain required a depth of inundation between 0.1 to 0.5 m, a duration of a minimum of 25 days and less than three years between satisfactory inundations (Kleynhans *et al*., 2007). Additional aids to interpreting the role of flow in structuring floodplain plant communities may include comparing historical with present day aerial photographs and relating changes through time with the flow regime (McOsker, 1998).

Box 4.1
River floodplains

As water flows onto dry floodplains, terrestrial vegetation is inundated and much of it dies. The nutrients released by this fuel the growth of plants that can cope with the new watery conditions: submerged and floating species that flourish in the quiet waters. Fish move from the river to the floodplain and spawn, using the shallow warm waters as nurseries for their juveniles. Water birds and swamp-loving mammals and herpetofauna follow. Growth is fast, with productivity linked to the extent, timing and duration of inundation. Welcomme (1985) showed that fishery production is proportional to the extent of inundation, with large African rivers that have extensive floodplains generally supporting highly productive fisheries – yielding up to 143 kg ha^{-1} year^{-1}. As river flow drops at the end of the wet season water drains from the floodplains, the fish move back into the river, aquatic plants disappear and terrestrial grasses and other floodplain vegetation grow again. Livestock and wildlife move onto the drying floodplain, grazing the abundant vegetation provided by the fertile soils. This timeless cycle has long supported three groups of subsistence users of floodplains: fishers, pasturalists with their livestock, and flood-recession agriculturalists, who share the resource by partitioning the time they annually use the floodplain.

Floodplains thus play an important role in the ecological integrity of the river and the rural economies of many countries in developing regions. The flow parameters outlined in Section 2.3.4 play a key role in maintaining these floodplains, determining, through their hydraulic influence, floodplain structure and functioning.

Magnitude and Duration:	The spatial and temporal extent of inundation of floodplains The water depths and current speeds on the floodplain The mosaic of accretion and erosion of sediments on the floodplain
Frequency:	The cycle of recurrence of wetter and drier years and seasons, and the number of times the floodplain may be wetted within any one year
Timing and Predictability:	The onset and termination of inundation and drying phases on the floodplain, and the surety with which each begins and ends
Rate of change and variability:	The rate of change of the flood hydrograph, which dictates the rate at which floodplains will flood and drain

The above natural characteristics of the flow regime are the driving force determining the nature of floodplain plant and animal species. Their rhythms of life have evolved over millennia to optimise prevailing river/floodplain conditions, and in doing so have come to provide one of the richest and most productive ecosystems upon which humanity relies.

Table 4-1 Seven suggested zones of riparian vegetation related to inundation regime (Boucher, 2001)

Location	Vegetation Zone	Inundation Interval	Abbreviation		Marker
					Debris Line
Drybank	Back Dynamic Zone	Approx. > 20 year floods	BD		
	Tree-Shrub Zone	2-20 year floods	TS		
	Lower Dynamic Zone (Transitional)	Within year floods	LD		Bottom Drybank Top Wetbank
Wetbank	Upper Wetbank Zone	Within season freshes	UWB		
	Lower Wetbank Zone	Wet season baseflow/Dry season freshes	LWB		
Aquatic	Rooted Aquatic Zone	Dry season baseflow	RAq		Perennial Free Water
	Floating Aquatic Zone	Perennial free water	FAq		

Table 4-2 Tentative guidelines for the biological reference condition of Riparian Scrub vegetation communities on the banks of Western Cape headwater streams (Reinecke *et al.*, 2007)

Attribute	**Vegetation communities**			
	Wetted Edge	**Channel Fringe**	**Tree Shrub**	**Outer Transitional**
Species richness	6.1 ± 4.2	9.1 ± 5.9	8.8 ± 2.9	19.9 ± 7.9
Equitability (H)	per 50 m^2 plot: 2.38 ± 0.23			
Relative diversity (J)	per 50 m^2 plot: 0.77 ± 0.06			
Growth form	• Sedges most common • Restios common • Rushes present but very rare • Adult Riparian Scrub trees very rare • No large tree species	• Restios most common • Sedges and shrubs rare • Rushes present but rare • All life stages of Riparian Scrub trees rare • No large tree species	• Sedges, restios and shrubs very rare • Rushes absent • Adult Riparian Scrub trees common • Large tree species very rare	• Most growth forms present at low frequency • Rushes absent • Small shrubs most common to this assemblage type • Riparian Scrub trees less common • Large tree species rare
Possible indicator species	*Isolepis prolifer* prolific *Prionium serratum* common *Calopsis paniculata* very common *Elegia capensis* very rare	*Calopsis paniculata* very common *Elegia capensis* very common *Erica caffra* common *Isolepis prolifer* common *Diospyros glabra* very rare *Morella serrata* and *Metrosideros angustifolia* seedlings common *Morella serrata* juveniles common	*Calopsis paniculata* very common *Elegia capensis* very common *Erica caffra* common *Isolepis prolifer* very rare *Diospyros glabra* common *Metrosideros angustifolia* adults prolific; juveniles common *Brabejum stellatifolium* adults common *Morella serrata* adults and juveniles common	*Elegia capensis* and *Calopsis paniculata* rare *Erica caffra, Prionium serratum,* and *Isolepis prolifer* absent *Diospyros glabra* very common *Pteridium aqualinum* common *Rhus angustifolia* rare but most common to this assemblage type All life stages of *Morella serrata, Metrosideros angustifolia, Brabejum stellatifolium* and *Brachylaena neriifolia* rare

Table 4-3 Comparison of vegetation communities of Reinecke *et al.* (2007) and Boucher (2001)

Reinecke *et al*	**Boucher**
Wet Edge	Lower Wetbank
Channel Fringe	Upper Wetbank
Tree Shrub	Tree Shrub
Outer Transitional	Back Dynamic

4.4 Fish and invertebrates

Three different approaches have been used in South Africa to assess the direct effects of hydraulic changes in the water column on aquatic organisms: Habitat Suitability Criteria (HSC), Flow Classes, and Hydraulic Biotopes. Although they could in principle be used for other ecosystem groups, they have mostly been used to study and describe the hydraulic habitat of fish and aquatic invertebrates. The three approaches are outlined below.

4.4.1 Habitat Suitability Criteria

The North American approach of deriving HSCs as part of the Physical HABitat SIMulation (PHABSIM) model (Bovee, 1986; Milhous *et al.*, 1989) was developed for defining the hydraulic habitat most commonly used by any selected river species. It is still widely used worldwide (Tharme, 2003). It was the first method to be tested by South African river ecologists for use in local rivers, in what was probably also the first attempt to apply this method outside the United States (Arthington and Zalucki, 1998). It entails collecting data on depth, velocity and substratum particle size wherever a species of interest is found in a study river, and using these to create HSC that together describe the most commonly-used hydraulic habitat conditions for the species.

Site selection

One of the principal challenges of deriving HSC for any given species is *transferability*, i.e. the ability of HSC developed with data from one river to predict habitat quality in other rivers and therefore, by implication, whether or not the species of interest would be found there. The suitability of new rivers cannot be ascertained, however, if their hydraulic conditions did not exist in the original one and thus were not captured in the HSC. By example, it would be inadvisable to use HSC developed for a tributary system to assess if suitable habitat was present on the mainstem river because depths and velocities would likely be quite different in the mainstem. Different hydraulic conditions do not necessarily mean the species will not occur in both the tributary and mainstem, for it may exist in both places, with one place possibly representing optimal conditions and the other sub-optimal ones.

Sites for characterising habitat conditions of a species should therefore include the broad range of habitats that are representative of all or most of the conditions a species will encounter. If this is not possible, data for HSC can be pooled from different sites and a range of discharges, although the resulting models may be more general and less precise (Hayes and Jowett, 1994). Sites to be used for constructing HSC should consist of both *representative reaches*, where conditions commonly found are well represented, as well *critical reaches* that contain unique or rare habitat types such as spawning or feeding habitat that are essential for the persistence of the species. These criteria for site selection need to be weighed against the more practical considerations of budget and time constraints and accessibility.

Selection of indicator species

Deriving HSC is time-consuming and it is not feasible to derive them for every species in a river. The selection of representative species is therefore an essential step in the process. This is a complex activity in its own right (King and Tharme, 1994). One approach could be to group the total suite of species into habitat guilds (e.g. Leonard and Orth, 1988; Aadland, 1993; Vadas and Orth, 2000; Persinger, 2003) and then choose one or more species to represent each guild. The following guilds are suggested by Kleynhans (2008) for South African fish species:

- *Rheophilics*: requiring flowing water:
  Fast-rheophilics: requiring fast flow (>0.3 m s^{-1}) during most phases of the life cycle
  Slow-rheophilics: requiring slow flow (<0.3 m s^{-1}) during most phases of the life-cycle
  Semi-rheophilics: requiring flowing water during certain phases of the life-cycle:
    - *Fast-semi-rheophilics*: requiring fast flowing water (>0.3 m s^{-1}) during certain phases of the life-cycle
    - *Slow-semi-rheophilics*: requiring slow flowing water (<0.3 m s^{-1}) during certain phases of the life-cycle
- *Limnophilics*: no particular flow requirements during any phase of the life. Water level may be important at times, however, to provide particular cover features during certain life-cycle stages.

For macro-invertebrates, guilds may be chosen on a similar basis, or similar life-history or feeding guilds may be chosen. Representative species for each should be chosen on the basis of those that have quite specific hydraulic-habitat requirements since they are likely to be most impacted upon by habitat changes.

Most representative species are chosen, and their HSC described, at the species level. Different life stages of any one species may have different hydraulic dependencies, however, leading to some authors suggesting that each such life stage should be treated as a separate 'ecological species' (Polis, 1984). Little work of this nature has been done in South Africa but it is a research topic needing urgent attention in order to manage future flows in a way that support all life-cycle stages of valued species.

When HRC exist for more than one species in a river it may be difficult to reconcile them to produce one managed flow regime that best supports all the organisms. Ways to resolve this include undertaking a risk analysis, such as the one suggested by Davies and Humphries (1995: cited in Arthington and Zalucki, 1998); building intra- and inter-annual variability into the recommended flow regime thereby mimicking the natural system (Arthington and Zalucki, 1998); or identifying the discharge at which habitat for the majority of species in a community declines sharply (e.g. King and Tharme, 1994) and maintaining flows above it.

Collecting fish and macro-invertebrate habitat data

Collecting data for HSC involves measuring the habitat variables of interest at the precise location where the organism was observed or sampled. As straightforward a task as this may seem, the difficulty of quantitative sampling in rivers, the heterogeneous nature of river habitats, and the mobility of river organisms themselves make this especially challenging (Heggenes, 1996). Gore and Nestler (1988) and Heggenes and Saltveit (1990) suggested that data should be collected at median flows since the reliability of the predictions is likely to decrease at very low and very high discharges, whilst King and Tharme (1994) recognized the need for developing different HSC for different seasons. Bovee (1986) suggested approximately 150-200 observations per target species, but more realistically Tharme and King (1994) suggested a number of not less than 35 where time and womanpower are limited.

Data for benthic invertebrate HSC are collected using either a surber or box sampler on rocky river beds, or a corer in sandy areas (e.g. Jowett and Richardson, 1991; King and Tharme, 1994). The data can either be recorded as presence/absence of a target species at a locality, or abundance of a species per sample. As there may be many invertebrate species in the sample, it would be necessary to select representative species or families for the HSC compilation. Alternatively, HSC can be developed to reflect the hydraulic habitat conditions linked to varying levels of community diversity rather than to individual representative species (King and Tharme, 1994).

Although collecting HSC data for invertebrates is more time-consuming and expensive because of the amount of laboratory work involved in identifying them (King and Tharme, 1994), it is considerably more difficult to collect HSC data for fish because of their larger sizes and greater mobility. A wide variety of fish-sampling methods is available, but not all are suited to the task. Most netting methods, including gill netting, fyke netting and seine netting collect fish over a wide area and are therefore imprecise in terms of highlighting the specific conditions used by any one species. These methods can, however, be useful for assigning broader habitat Flow Classes to a species (Section 4.4.2). Snorkelling is the least intrusive method for obtaining HSC data if conditions permit, since the fish remain relatively undisturbed and the errors associated with observer bias are minimised (Bain *et al*., 1985; Heggenes *et al*., 1990; Pert *et al.*, 1997). The main drawback to snorkelling is that it is only possible in relatively small rivers with a low discharge and high visibility; it is ineffective in deep rivers, or where turbidity impairs underwater visibility. If snorkelling is not possible, electrofishing, either using a back-pack generator or by pre-positioned-area electrofishing (Walsh and Fenner, 2002), is a viable method although it causes considerable disturbance to fish (Heggenes e*t al.*, 1990). For large-bodied fish in bigger river systems, radio- or acoustic-telemetry methods are the only feasible alternatives for collecting accurate habitat data (e.g. Scruton *et al.*, 2002).

Once the locations and abundances of the selected invertebrate or fish species have been recorded, the hydraulic-habitat variables of interest, most commonly water depth, velocity, substratum particle size and sometimes cover, can be measured and recorded at the same localities. Usually, velocity is recorded as depth-averaged, since this is the form used by hydraulic models. Substratum particle size can be measured directly or as dominant and sub-dominant particle sizes (Bovee, 1986). These measurements represent the conditions in which the species was found, but it might be useful to also measure the range and proportions of different kinds of hydraulic habitat available, because species may not be positioned in the most common habitat and may even be using a habitat that is very rare. Measurements of both *used* habitat (i.e. where the species is found) and *available* habitat (i.e. how much of a range of habitats is available) can be combined to produce measures of *preferred* habitat. This is a contentious statistic that is dealt with in detail by Pollard (2000). Available habitat can be measured through random, stratified random or proportional sampling of depths, velocities and so on, as discussed comprehensively by Bovee (1986), King and Tharme (1994) and Pollard (2000).

Categories of Habitat Suitability Criteria curves (HSC)

HSC translate the collected hydraulic and geomorphological data on habitat into quantitative indices of habitat quality for the relevant species (Bovee, 1986). The fundamental assumption of these models is that organisms will favour, and therefore be associated more frequently with, habitat conditions that promote their survival growth and reproduction (Freeman *et al.*, 1997), and that these conditions have definable limits (De Graaf and Bain, 1986). They have been variously referred to as 'habitat suitability curves' (Jowett *et al.*, 1991); 'preference curves' (Armstrong *et al.*, 2003); 'habitat preference criteria' (Nykänen and Huusko, 2004); or 'habitat suitability indices'. The term Habitat Suitability Criteria (Bovee, 1986; Ahmadi-Nedushan *et al.*, 2006; Hardy *et al*., 2006) is used here since habitat selection may not always be represented by means of response 'curves'.

There are three ways of deriving HSC for species or communities):

- *Category I criteri*a: where there are no field data, HSC may be obtained for the specific species or its nearest available equivalent from HSC libraries, from the literature, or created using professional experience
- *Category II criteria* or 'utilisation functions' are created from data collected in the field; they take the form of a frequency distribution for each measured hydraulic variable, which describes abundance of the species over the range that the variable was measured
- *Category III criteria* or 'suitability functions' express habitat use as a proportion of the amount of habitat available (see last section).

A brief overview of the derivation of HSC is provided in the following section. For more comprehensive step-by-step descriptions the reader is referred to King and Tharme (1994) and Waddle (2001).

Basic principles for creating HSC

Arranging and interpreting the data

HSC data can be depicted in a number of ways. Most commonly, they are plotted as a frequency histogram (see below), or as an x-y scatter plot with the number of observations or abundances of the organism on the dependent axis and the habitat variable on the independent axis, with a polynomial function fitted (e.g. Jowett and Richardson, 1990).

Creating frequency distributions

A frequency distribution is plotted for a species for each measured hydraulic-habitat variable; these variables are most commonly depth, velocity and substratum. Each hydraulic variable is first apportioned to classes, guided by methods that calculate the appropriate number of classes (King and Tharme, 1994). The frequencies of the species are usually represented by the number of individuals occurring in each class of the variable (e.g. how many fish species A were at a depth of 30-50 cm), or by the total number of observations of that species per class (e.g. how many records of fish species A were taken at a depth of 30-50 cm). The distributions are then smoothed either by hand, by means of a curve-fitting function, or by kernel-density estimation and then normalised, that is, expressed as a value between 0 (least favourable habitat) and 1 (optimal habitat) (Bovee, 1986).

Category II criteria may be biased by the proportion of the total amount of habitat available in the river, and may be converted to Category III criteria by expressing habitat selection as a proportion of the amount of habitat utilised to the amount of habitat available:

$$E = \frac{U}{A} \tag{4.1}$$

where E is the index of electivity; U is the relative frequency of fish observed in a particular habitat interval; A is the proportion of the total area represented by that habitat interval (Waddle, 2001).

Two points are worth noting here. First, the term 'electivity' is used here rather than the more common term 'preference'. Since factors such as the presence or absence of competitors or predators in different rivers may also influence habitat selection, an organism's choice of hydraulic conditions in any particular river may not always reflect its true preference (Rosenfeld, 2003). Second, the inclusion of habitat availability (A) in Category III criteria has been criticised because it introduce biases of its own (Pollard, 2000). Collecting availability data is also time and data intensive and may therefore not always be possible. A degree of experience and professional judgement is required to decide whether it is appropriate to represent habitat as a 'utilisation' or an 'electivity' function and the reader is referred to King and Tharme (1994); Pollard (2000), Paxton (2008) and Paxton and King (in press) for further discussions.

Whatever the case, it may still be instructive to compare the relative proportions of available and selected habitat on one graph, as has been done for juvenile Clanwilliam yellowfish (*Labeobarbus capensis*) (Figure 4-2). If the 'optimal habitat' range is defined as having a utilisation index >0.85 (Waddle, 2001), then from Figure 4-2 the optimal velocities for juvenile yellowfish, that is, the conditions where they were most commonly found, are shown as being in the range of 0.1-0.5 m s^{-1}. Comparing the utilisation curves with the availability curves suggests that juvenile yellowfish selected marginally greater depths and much higher velocities than were most commonly available in the river at the time of sampling. That juvenile yellowfish elected to use these conditions over others is suggested by the fact that less than 50 % of the available velocity range fell within the optimal range that they used. Similarly for substratum, despite that fact that sand (<2 mm) was by far the most common substratum class in the river, juvenile yellowfish were found most frequently in areas where small cobble was present (64-120 mm).

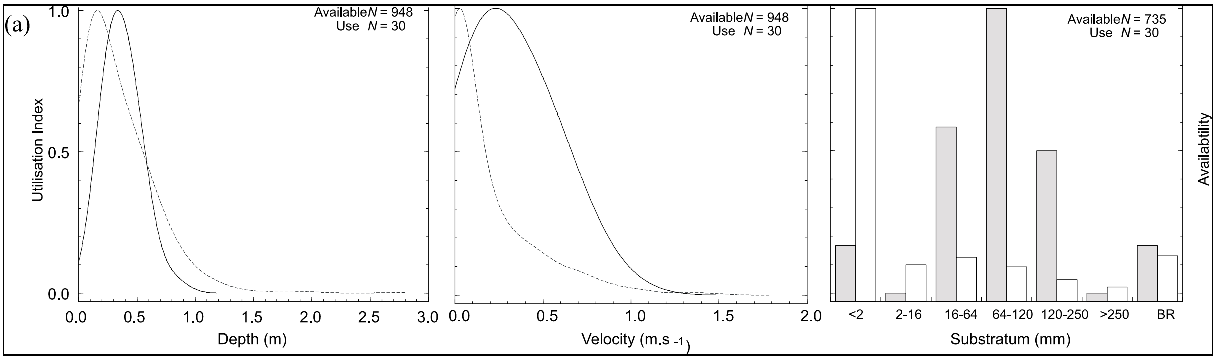


Figure 4-2 Category II HSC for juvenile Clanwilliam yellowfish (*Labeobarbus capensis*) from the Driehoeks River, Western Cape (solid black lines and shaded bars). Habitat availability (*A*) (secondary *y* axis): broken lines and unshaded bars (Paxton and King, in press)

Strengths and limitations of HSC

HSC have been applied and tested worldwide and offer one of the most sophisticated, precise and repeatable methods for quantifying physical habitat used by river organisms. Their usefulness lies in the fact that they can provide input to hydraulic models that predict discharge-related conditions using the same variables. The two kinds of data – simulated hydraulic conditions from the hydraulic model and known optimum habitat from the HSC – together provide insight into how optimum hydraulic habitat for any species of interest can change as flows change.

Single sets of HSC cannot represent the full conditions that are optimal for a species. Different life stages or different size individuals may have different habitat requirements, and different habitat might be used per season or by day and night. By example, Golden Perch in the Murray Darling Basin, Australia, use deep habitats in the day but shallow waters at night (Crook *et al.*, 2001); even though shallow habitats may provide greater food resources, they are also areas of greater predation by birds during the day and so the fish are forced into deeper than optimum waters. Similar diel movements were recorded for the Clanwilliam sawfin *Barbus serra* in the Driehoeks River, Western Cape (Paxton and King, in press). Finally, habitat studies focus on instream hydraulic conditions, and habitats outside of the active channel may be essential for a species. For example, net-winged midge adults lay their eggs during the low-flow season on exposed portions of boulders within the channel that will be inundated during the following wet season. Vondracek and Longanecker (1993, in Railsback *et al.*, 2003) reported that habitat selection by trout varies with such factors as temperature and day length. Critical habitat areas, such as those used for feeding, may be inhabited for small amounts of time or cover small areas but will still be vital for life support. All of these factors point to the fact that even HSC created using large amounts of data will still usually be a gross simplification of the habitat a species needs for survival.

Railsback *et al*. (2003) suggested that habitat quality might be a better descriptor than empirical measurements of habitat selection, because this describes the extent to which an environment provides the conditions that would maximise the fitness of individuals, by maximising growth potential and minimising mortality risk. Habitats with the highest densities of individuals, that is, those that are selected by most, are not necessarily those that have the highest fitness value. A habitat with low mortality risk but only a small amount of food, may provide the best quality habitat, but only for a few dominant individuals. The bulk of the individuals may be forced to occupy habitat with a higher mortality risk but more food. This criticism applies to all habitat models, not just HSC. An example of this principle is provided by two invertebrate species. Blackfly (Simuliidae) in the Molenaars River, Western Cape, selected different individual stones in the presence and absence of their caddisfly competitor, *Cheumatopsyche afra* (Figure 4-3). Several studies have suggested that the habitats of these taxa overlap, and that caddisflies are the superior competitor. After an initial collection of the invertebrates present per stone, the stones were replaced in exactly the same locations and a further collection was made after one month. The caddisflies, with their relatively low mobility, were not able to recolonise any of the denuded stones within this time period, but the highly mobile Simuliidae were able to do so. Simuliidae density increased dramatically on stones that previously supported higher *C. afra* numbers, although the population density as a whole did not change significantly.

Thus a major component of habitat-selection studies must be ecological investigation of the mechanisms behind habitat use, and of how the major fitness criteria, such as growth, survival, and reproductive success, depend on habitat characteristics. Without this, habitat-selection studies may yield unreliable results (Railsback *et al.*, 2003).

HSC have not been widely used in South Africa, principally because they target individual species and are data- and time-intensive (King and Tharme, 1994). They remain, however, a valuable means of investigating flow-species relationships and if the protocols outlined above are adhered to, they only need to be derived once for a single species and can then be stored in and retrieved from online databases such as the one administered by the United States Geological Surveys, National Wetlands Research Centre (http://www.nwrc.usgs.gov/ wdb/pub/hsi/hsiindex.htm), thereby providing a valuable resource for future scientists and managers.

In South Africa, where the major demand for this kind of work has been as input to Environmental Flow Assessments, more focus has been placed on the search for simple, inexpensive yet definitive hydraulic units that describe the living space of biological communities. Two alternative approaches being developed in South Africa, Habitat Classes and Hydraulic Biotopes, are presented below.

4.4.2 Flow classes

Where time and funds are limited, semi-quantitative rules and generalisations for broad categories of hydraulic habitat may be useful. Flow Classes, formerly referred to as habitat classes, offer such an alternative. Flow Classes were initially developed by Oswood and Barber (1982) and adapted for South Africa for fish by Kleynhans (1999) and for invertebrates by Jordanova *et al*. (2004) and Hirschowitz *et al.* (2006). As with HSC, they are described in terms of key hydraulic parameters such as depth, velocity and substratum particle size.

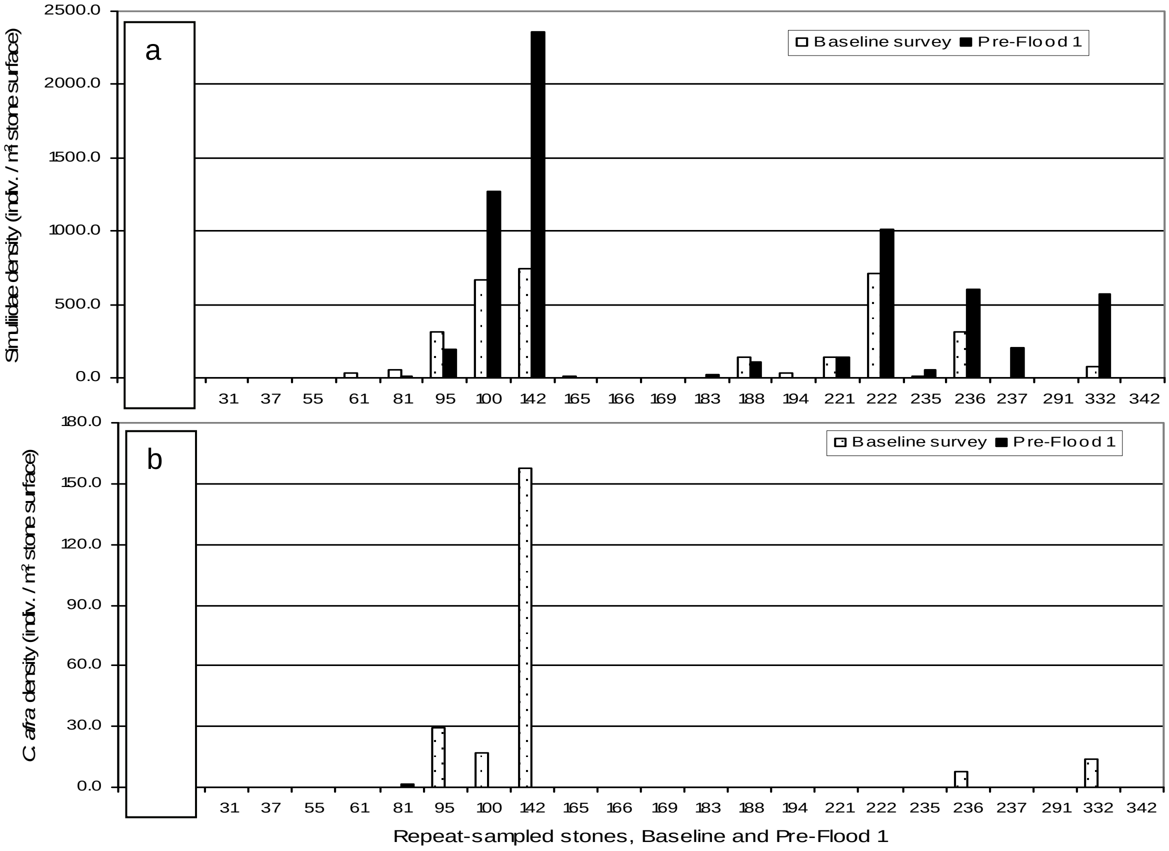


Figure 4-3 Density of a) blackfly (Simuliidae) larvae and b) their competitor *Cheumatopsyche afra* on individual stones that were repeat-sampled at an interval of one month (unpub. data G. Ractliffe, University of Cape Town). Baseline: spotted bars; after one month: black bars

Flow Classes for fish

Whereas HSC are created from empirical data of where an organism was found, Flow Classes are broad, pre-defined, discrete categories of velocity and depth that are thought to be relevant for the various groups of organisms. Based on knowledge of habitat requirements of 134 species of indigenous freshwater fish, a panel of experts predefined four Flow Classes: slow-shallow; slow-deep; fast-shallow and fast-deep (Table 4-4; Figure 4-4). As in the case of the HSC, the selection of target or indicator species to represent the full suite of guilds in the fish community is sometimes advisable. The same selection criteria as outlined in Section 4.4.1 (a) can be applied.

Table 4-4 Flow Classes for fish and suggested method for data collection (Kleynhans, 1999)

Class	Velocity	Depth	Description	Sampling method
SS	Slow (<0.3 m s^{-1})	Shallow (<0.5 m)	Shallow pools and backwaters	Small seine or electroshocking
SD	Slow (<0.3 m s^{-1})	Deep (>0.5 m)	Deep pools and backwaters	Large seine or cast net
FS	Fast (>0.3 m s^{-1})	Shallow (<0.3 m)	Shallow runs, rapids and riffles	Electroshocking
FD	Fast (>0.3 m s^{-1})	Deep (>0.3 m)	Deep runs, rapids and riffles	Electroshocking

In this classification, each Flow Class is associated with a specific type of morphological unit, such as backwaters or riffles and with an appropriate sampling method. In addition to the flow-depth classes, there are four categories of cover that are important for fish (Table 4-5).

These Flow Classes for fish and are now widely used in assessments of the South African Ecological Reserve and Present Ecological Status (Kleynhans, 2003; Kleynhans and Louw, 2007).

In summary, the South African fish Flow Classes are very broad, with only two classes for velocity: less than or greater than 0.3 m s^{-1} (Table 4-4). Lamouroux *et al.* (1999) described five velocity classes for fish: 0-0.05; 0.05-0.2; 0.2-0.4; 0.4-0.8 and >0.8 m s^{-1}. This could lead to alternative thresholds or more Flow Classes needing to be defined, as suggested by Niehaus *et al.* (1997) and Paxton and King (in press). It should be noted that several additional fish classes can be added to the South African fish Flow Classes if the information is available. These include: slow-very shallow (<0.1 m deep), fast-very shallow (<0.1 m deep) and fast-intermediate (0.2-0.3 m deep). Future monitoring of the Reserve will take these additional classes into consideration (*pers. comm.* Dr N Kleynhans, Institute for Water Quality Studies, Pretoria).

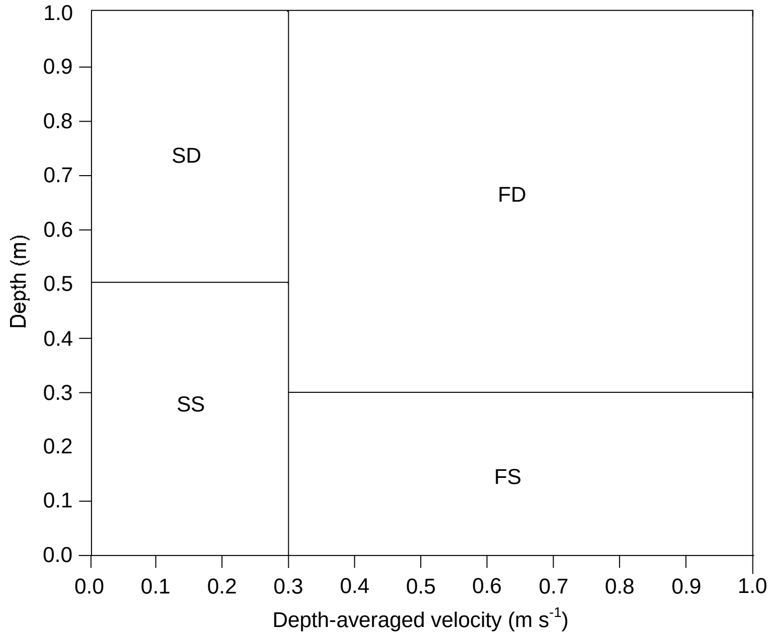


Figure 4-4 A graphical representation of Flow Classes for fish in South Africa: SD = Slow Deep; SS = Slow Shallow, FD = Fast Deep, FS = Fast Shallow (Kleynhans, 1999)

Flow classes for invertebrates

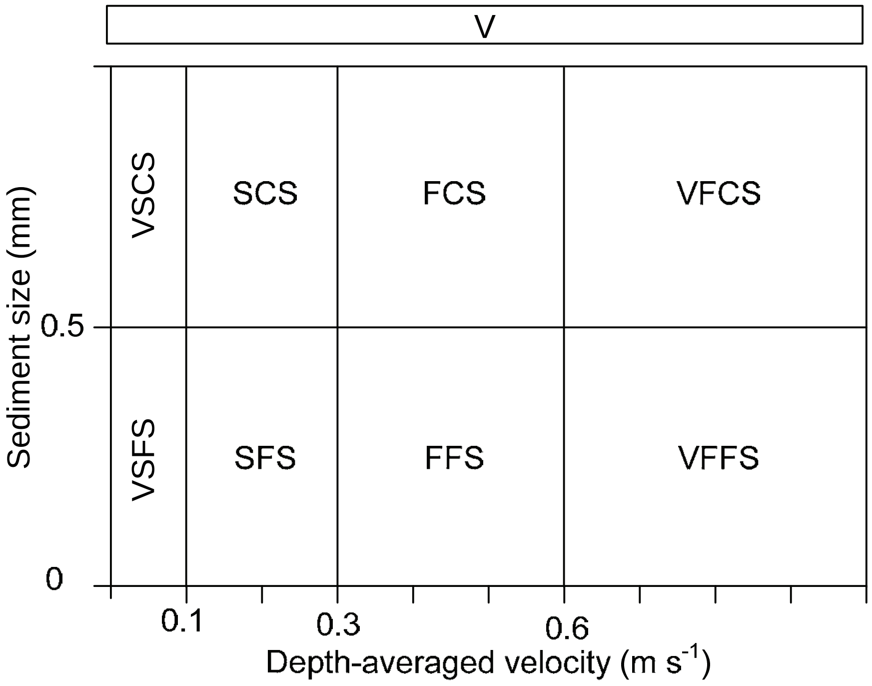
Five Flow Classes for invertebrates were developed by Jordanova *et al*. (2004). These were defined in terms of depth-averaged velocity, substratum type and vegetation. Subsequently these Flow Classes were further subdivided to cater for very fast and very slow flow velocities (Hirschowitz *et al.*, 2006) (see Figure 4-5).

Table 4-5 Cover type (Kleynhans, 1999) after Wang *et al.*,(1996)

Cover	**Description**
Overhanging vegetation	Marginal vegetation overhanging water by ~0.3 m-< 0.1 m above the water surface
Undercut banks and root wads	Banks overhanging water by ~0.3 m-< 0.1 m above the water surface
Substratum	Substratum particles: rocks, boulders, cobbles, gravel, sand, fine sediment, woody debris
Aquatic macrophytes	Submerged and emergent water plants

Application of Flow Classes

Each HSC depicts a single variable as a continuous range of values, illustrating the suitability of all parts of that range as habitat for a species. Flow Classes, on the other hand, depict defined boxes of conditions, with any one box being either suitable (1) or unsuitable (0) habitat for a species. These suitability values can be linked to hydraulic models in the same way that HSC are, to transform model predictions of hydraulic conditions into indices of habitat quality. For this purpose, Hirshowitz *et a*l. (2006) used the flow classes shown in Figure 4-4 and Figure 4-5 to develop preference files in the software format required by the River2D hydraulic model. Once these are entered into the model, the habitat conditions in a reach are expressed as the proportion of the inundated channel width (or area if it is a two-dimensional model) that falls within a particular Flow Class. This is an index of relative availability (Birkhead, 2008), and a judgement then has to be made by the ecologist to what proportion of loss, such as 50 % or 25 %, will have a significant impact on the species or community being considered.



Notes: VSFS: very slow over fine sediment; SFS: slow over fine sediment; FFS: fast over fine sediment; VFFS: very fast over fine sediment; VSCS: very slow over course sediment; SCS: slow over course sediment; FCS: fast over course sediment; VFCS: very fast over course sediment; V: flow through vegetation

Figure 4-5 Proposed flow classes for invertebrates in South Africa: (Hirshowitz *et al.*, 2006)

Strengths and limitations of flow classes

Flow Classes offer considerable advantages in that they are semi-quantitative and the data required to allocate a species or life stage into one of the classes can be collected relatively easily compared with the amount of effort required to construct HSC. Flow Classes are also compatible with hydraulic models. Their principal disadvantage is that not all fish species will perceive habitat in the way depicted in the fish Flow Classes (Paxton and King, in press), and the same holds for invertebrate species. Required habitat may thus be under or over-estimated and critical habitats ignored.

The ecological relevance of the Flow Classes has been derived from data on relatively few species, and more species need to be included leading to a re-assessment of appropriate class intervals

4.4.3 Hydraulic biotopes

Another approach to describing hydraulic habitat employs the concept of hydraulic biotopes (HB) (Section 2.3.1). In its original form, as proposed by Dahl (1908), a biotope was defined as a set of relatively uniform physical and biological conditions, together with the distinctive biological community associated with it. Thus, whereas a habitat defines the living conditions of a species, biotope defines those of groups of species – a community (Olenin and Ducrotoy, 2006). The concept of biotope has been adopted and modified somewhat by river ecologists in South Africa, to signify the relatively small-scale, visually distinguishable, patches of hydraulic conditions in a river reach – the hydraulic biotope. These may or may not have distinctive communities of plants and animals. They nevertheless provide a means of classifying hydraulic habitat, using a combination of visually identified flow types (refer to Table 2-3) and substratum types (bedrock, boulder, cobble, gravel, sand, silt). The hydraulic biotope concept was developed in South Africa by geomorphologists (Rowntree and Wadeson, 1999; Wadeson and Rowntree, 2001), who described the physical properties of the hydraulic biotopes they recognised, and by ecologists (King *et al.*, 1996; Pollard, 2000; King and Schael, 2001) who examined their relevance for invertebrate and fish species in Western Cape headwater streams. King and Schael (2001) harmonised the two approaches in a table that listed all geomorphologically recognised hydraulic biotopes into a smaller set that was seen as having distinctly different invertebrate communities (Table 4-6). They also provided summary hydraulic statistics for each ecological HB (Table 4-7).

Table 4-6 Geomorphological Hydraulic Biotopes (HB) grouped by Ecological HB (King and Schael, 2001)

Geomorphological HB	Ecological HB
backwaters, slack waters, pools, slow glides	pools
runs and fast glides	runs
riffles	riffles
rapids, cascades, chutes, waterfalls, boils	rapids

The scale of their hydraulic biotopes can vary from less than 0.5 m^2 to that of a morphological unit depending on the complexity of the river bed and flow patterns.

The approach offers both cost-effectiveness and a spatially-explicit product – addressing perceived weaknesses of the existing 1D and statistical hydraulic models (Pollard, 2000; King and Schael, 2001). Unlike the previous two approaches, however, which are compatible with hydraulic modeling, no means exist yet for transforming the output of hydraulic models, that is depth and velocity predictions for a range of discharges, into predictions of the hydraulic biotopes that would be present.

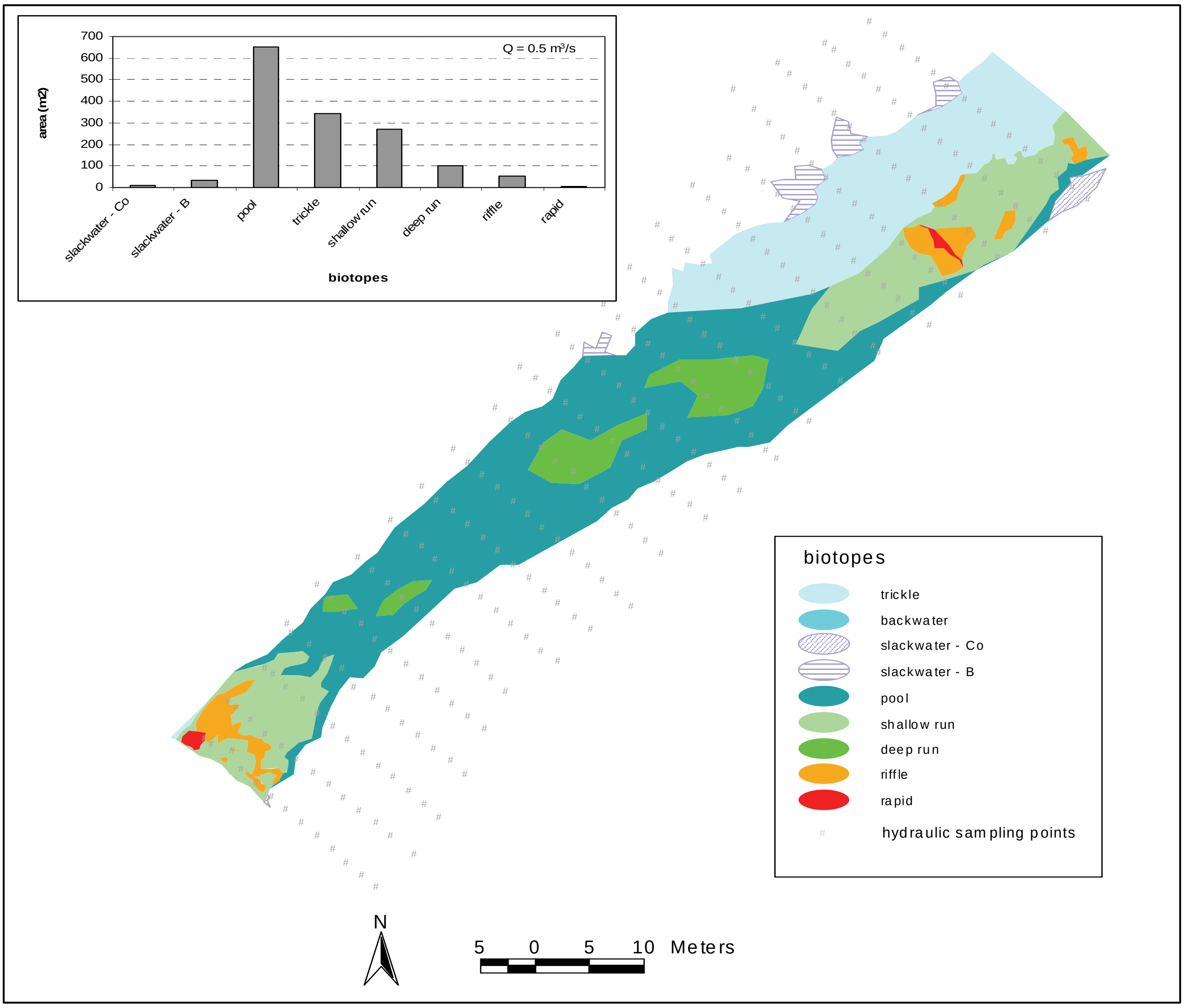
Mapping hydraulic biotopes

Flow types and substratum types are mapped, either by hand in the field and later digitised, or hand drawn maps are combined with digitised coordinates recorded on-site using a differential GPS. The maps describe the mosaic of flow and substratum types in a river reach, and can be re-drawn at a range of discharges to illustrate how hydraulic conditions change. King and Schael (2001), for instance, described hydraulic biotopes for macro-invertebrates in defined river reaches by drawing at the river, and then digitizing, maps of substratum particle size and flow types. Schael (2006) also mapped two river reaches over a range of discharges to show how the hydraulic biotopes changed position and size and also investigated the influence this had on the invertebrate communities there.

Table 4-7 Definition of each biologically-defined hydraulic biotope (HB) in Western Cape headwater streams by depth (m), flow types, substrata, mean water column (0.6) velocity (m s^{-1}), and Froude number (King and Schael (2001). Flow-type codes as per Table 2.3

HB	Depth	Flow Description	Substrata	Mean Velocity	Froude Number	Comments
Rapid	shallow to deep: up to 0.70	turbulent, broken water: CAS, USW, BSW, CH, STR, FF, FRF, some fast RS	boulders and large cobbles	0.38-0.64	0.371-0.900	CAS is the dominant flow type; CH and FF are unique to this HB
Riffle	shallow: <0.30	fast, flickering flow: FRF, USW, BSW, CAS, some fast RS	cobbles and sometimes small boulders	0.27-0.39	0.332-0.425	FRF is the dominant flow type.
Run	shallow to moderately deep: up to 0.50	fast to moderately fast rippled flow: RS, SBT, some FRF	a range of substrata	0.05-0.19	0.070-0.200	RS is the dominant flow type.
Pool	shallow or deep: 0.03->1.00	slow, smooth flow: SBT, BPF, rarely NF	a range of substrata	0.00-0.10	<0.070	Bedrock and alluvial pools may have different species assemblages

An example of a biotope map produced for a site on the Berg River, Western Cape, at two discharges (0.5 m^3 s^{-1} and 2.5 m^3 s^{-1}), is provided in Figure 4-6 and Figure 4-7. The maps were drawn based on the distribution of flow types and substratum categories, to provide a plan view of the biotope mosaic over the extent of the site. Simultaneously, depth and velocity were measured along transects over the same portion of the river bed (grey dots in Figure 4-6 and Figure 4-7). The main difference between the seasons, as indicated in the two maps, is the predominance of the pool biotope in Figure 4-6 and of run biotopes in Figure 4-7, with loss of trickle biotopes, which are drowned out at the higher discharge. Overlaying the biotope maps with the cross-sections of point measurements of depth and velocity allowed for statistical testing of depth, velocity and derived hydraulic variables (Froude, Reynolds numbers, and unit stream power). These variables grouped according to the biotope within which they were measured. The more obvious cases, for example slackwater versus deep run, were statistically discriminated by all of the hydraulic variables. Biotopes that were more similar, however, for example run versus riffle, or riffle versus rapid, were discriminated by only some of the variables, and not consistently by any one. However, groupings of the visually defined flow types were consistently differentiated in terms of their hydraulic characteristics.

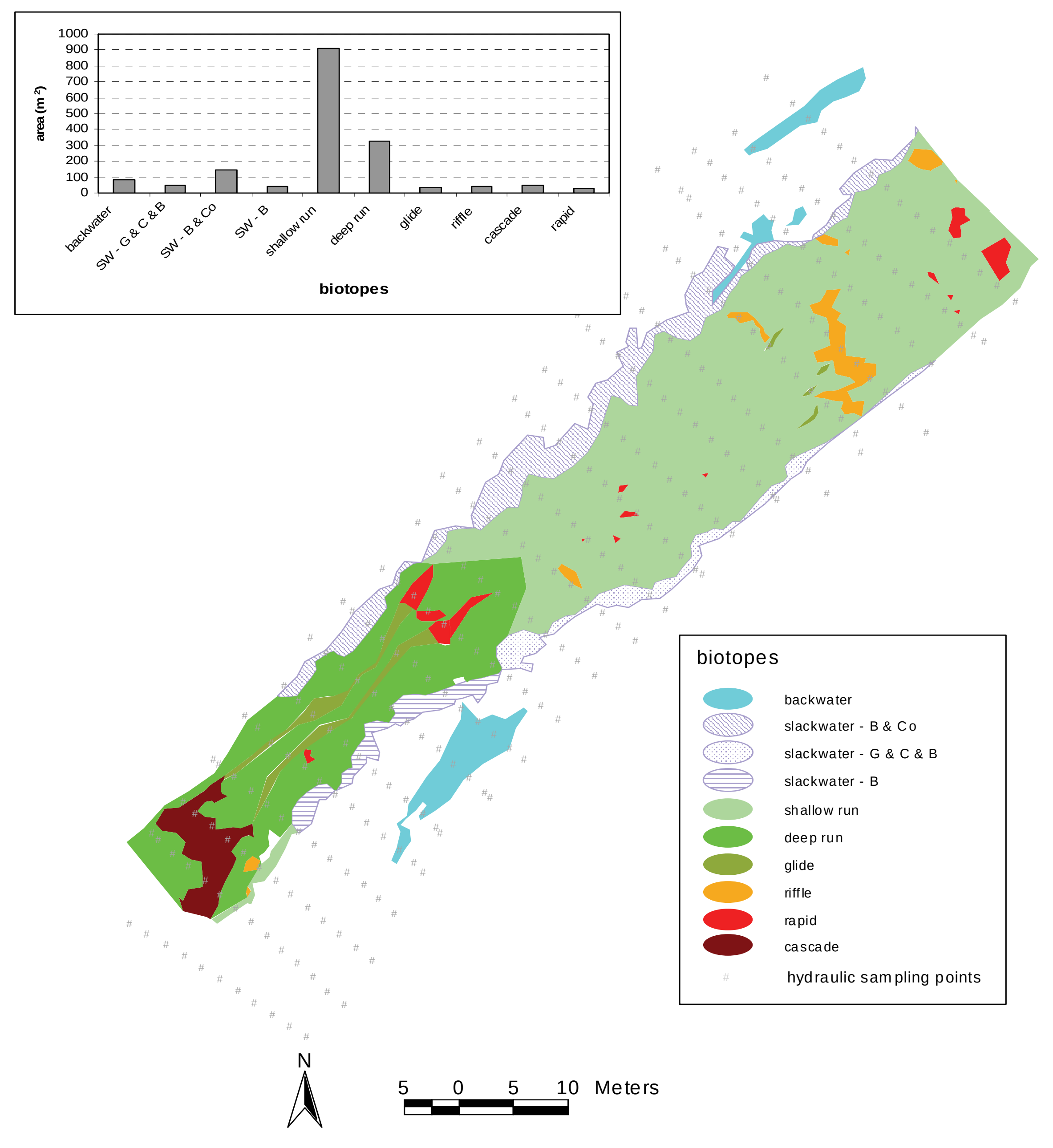


Note: Dotted lines represent transects where point-measurements of hydraulic variables were made, and used to evaluate the hydraulic characteristics of each spatially defined biotope.

Figure 4-6 Biotopes mapped in the upper Berg River in summer (Q = 0.5 $m^3 s^{-1}$). Inset bar graph shows the area of each biotope type in m^2.

The biological relevance of biotopes or visually defined flow types

It is relatively easy to identify and quantitatively describe discrete hydraulic units as above, but establishing their ecological relevance remains largely unaccomplished. This can be done by collecting fish or invertebrates within recognised hydraulic biotopes and correlating the two data sets. This was the focus of a single study on invertebrate communities in South Africa (King and Schael, 2001), which found that at a community level the full range of biotopes were not well correlated with distinct invertebrate assemblages. Flow classes (Section 4.4.2) were also not good predictors of invertebrate communities, because of the importance of substratum type as an additional discriminator. They did find, however, that modified flow classes (Table 4-6) combined with coarse substratum categories – boulder/bedrock; large cobble; pebble – did have unique invertebrate communities. Considerably more research, however, is required to identify relevant thresholds defining each ecologically-relevant hydraulic biotope.



Note: Dotted lines represent transects where point-measurements of hydraulic variables were made, and used to evaluate the hydraulic characteristics of each spatially defined biotope.

Figure 4-7 Biotopes mapped in the Berg River in winter (Q = 2.5 m^3s^{-1}), in the same reach as in Figure 4-6. Inset bar graph shows the area of each biotope type in m^2.

Strengths and limitations

The hydraulic biotope approach is especially useful in developing countries where data and expertise may be limited and a rapid assessment of the hydraulic nature of a river is required. It also has the advantage of being visually informative and providing a description of the river that is accessible to specialists from many disciplines. Its major drawback is that it is restricted to the mapping of biotopes for observed flows only and therefore has a limited capability of predicting how the distribution of biotopes would change with flow changes.

Attempts have been made to link hydraulic biotopes to basic hydraulic parameters such as depth and velocity as well as derived hydraulic parameters such as Froude number (e.g. Table 4-7). Padmore *et al.* (1998), Jowett (1993) and Wadeson (1994) found significant relationships between biotopes and hydraulic parameters. Froude number, the ratio of flow depth to the square root of velocity, was found to be the most relevant. Froude number, however, is a reach-scale property and may not therefore be a relevant descriptor of hydraulic biotope-scale features. Other researchers, such as Clifford *et al.* (2006), found little evidence of a significant relationship between hydraulic parameters and biotopes and warned against the use of Froude number, as a wide range of combinations of depth and velocity could result in the same Froude number. They concluded that attempts to link biotopes with ecological response and hydraulic properties are premature. Rowntree and Wadeson (1999) noted inconsistent use of the terminology leading to discrepancies between researchers and sites, which is a common problem with an emerging branch of science. Hydraulic biotopes clearly hold promise as a useful way of describing and studying river ecosystems, but much remains to be researched.

4.5 Boundary-layer, benthic and hyporheic flows

While the above methods account for a broad range of habitat types and scales, there are other aspects of habitat that are more difficult to measure and not well studied. For instance, flow around boulders on the river bed is much more complex than can be adequately described by means of the depth-averaged or near-bed velocity measurements commonly used in habitat studies (Davis and Barmuta, 1989; Hart *et al.*, 1996; Bouckaert and Davis, 1998) and so the true conditions experienced by organisms are not well defined. Invertebrate communities on the downstream side of boulders, for instance, may be more diverse and more abundant than those on the upstream side where shear and drag forces are greater (Bouckaert and Davis, 1998). It is also thought that small organisms take advantage of, and live in, the boundary layer of quieter flow immediately at the rock surface, but almost nothing is known of this.

Another aspect that has not received much attention in South Africa is the interaction of groundwater and surface runoff within the river bed, i.e. the hyporheos. This is an important area of exchange for water, nutrients and particulate organic matter and represents, in itself, a unique ecotonal environment supporting assemblages of mieo-invertebrates and the early life stages of macro-invertebrates. Elsewhere in the world, studies have shown that salmon select spawning sites based on the presence of hyporheic upwelling and down-welling zones (Geist *et al.*, 2002), and invertebrates are known to use the area as a refuge in times of flood (Hynes *et al.*, 1976), but almost no research on this important part of a river ecosystem has been done in South Africa.

4.6 Conclusion

The dynamic nature of river flow makes aquatic habitats transient features of any river landscape. The difficulty of quantifying these ephemeral phenomena and understanding the biological responses to them should be clear from the range of approaches that has been proposed for describing them and the limitations of even the most sophisticated methods. Characterising this extraordinary complexity presents considerable challenges for ecologists, geomorphologists and hydraulicians, particularly when data are few.

River flow can act either directly on an organism or indirectly through affecting some component of its habitat. Indirect effects can be addressed through studies of channel maintenance, floodplain inundation and sediment dynamics, bearing in mind that such features should be studied in a way that is ecologically relevant.

Relationships between river flow and riverine biota are presently studied through three main approaches: HSC, Flow Classes, and hydraulic-biotope mapping. HSC are compatible with hydraulic models and, despite their limitations their outputs are testable and predictive. Flow Classes are potentially useful in data-poor situations when the habitat of a species or life stage may only be understood in general terms. Their advantages are that they are semi-quantitative, can be applied on the basis of 'best-available-knowledge' and can be linked to hydraulic models. Hydraulic-biotope mapping provides an accessible form of information on the distribution of hydraulic habitats within a river reach in a way that is thought to be ecologically relevant. From the maps drawn they can be quantified by area per river reach and discharge, and their hydraulic attributes can be summarized in a fairly general way. They are not well understood hydraulically, however, and for this reason they are not presently compatible with hydraulic models. Whether or not they could be in the future is a topic for research, as are the flow types that partially define them.

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5. ECOLOGICAL ISSUES IN RIVER FLOW MANAGEMENT AND THE CHALLENGES FOR ECOHYDRAULICS

BR Paxton and JM King

5.1 Hydrology – the master variable

The daily, seasonal and inter-annual fluctuations in river flow, together with the changes it produces in channel form, structure the physical template that supports, and dictates the nature of, the living river ecosystem. Hydrological data describe these patterns of river flow, and simulations can be developed of daily, monthly or annual flow for any site along a river system, with the accuracy of these being dependent on the gauged rainfall, flow and other data available for calibration. The measured or simulated hydrological data provide vital insights into the overall nature of a river system: whether it is perennial or non-perennial in flow; if it is in a winter or summer rainfall area; if it has pronounced dry and wet seasons; if it exhibits flashy, short-lived flood flows or has a long, monsoonal flood season; and much more. Many traits of river organisms can be linked directly to such flow statistics, such as fish that migrate upstream on early floods or spawn during dry-season small floods. But many links to flow are more subtle, such as aquatic plants that need specific ranges of times when they are under water and emergent above water in order to complete specific stages of their life cycles. Whether or not the links to flow are obvious, in reality the riverine organisms are reacting largely to local *hydraulic* conditions rather than to flow *per se*, as discussed in the next section.

5.2 Hydraulics – the vital translator

Hydrological data on river flow inform on how much water moves through any chosen point along the river system over a chosen time period. Such data do not inform on the forces acting on the channel or on the conditions directly experienced by the biota. This is dealt with by the discipline of hydraulics.

Hydraulic techniques transform flow data into measures of water depth, current speed, area of floodplain inundated, shear stress, stream power and more – measures that explain where the water is, how fast it is moving, how deep it is, and how far up the bank a specific discharge reaches. This is vital information in the study of fluvial landscapes. Geomorphological features of rivers such as banks, sandbars, cobble beds and floodplains are sculptured by the forces acting upon them as water flows downstream. Faster-flowing water moves larger bed particles than does slower water, and so steeper channels tend to have boulder or cobble beds whilst flatter ones have gravel, sand or silt beds (Section 2.3.1). Specific flows overtop banks and flood riverine wetlands, pouring sediments onto floodplains and then retreating leaving nutrient-rich soils that support rich plant life (Section 2.3.3). Daily fluctuations in flow moisten the channel margin, supporting mosses and ferns that need damp but not inundated conditions. Seasonal fluctuations in flow support the sequence of vegetation communities up river banks (refer to Figure 3-3 and Figure 3-4) and across floodplains, enhancing biodiversity both among the plants and among the animals that inhabit such areas. Hydraulic conditions within the water column differ from the water surface to the river bed, with the slowest flow usually at the river bed, and from channel edge to mid-channel, with the slowest flow usually at the edge, and all of these change by minute, day, season and year as discharge changes.

Such combinations of hydraulic and geomorphological information are, in turn, vital information in ecological studies of the river ecosystem. Different aquatic animal species live in the full range of combinations of physical conditions: stones or mud; sandbars or riffles; quieter or faster water; or deeper or shallower flow conditions; all as their various evolved characteristics dictate.

Being able to measure the different hydraulic conditions within which different riverine species exist allows us to define their need for survival in terms of one of their most important environmental drivers – hydraulic habitat. It becomes possible to describe the conditions under which each species is most commonly found: the depth and speed of flow in areas it tends to inhabit, as well as other hydraulic descriptors such as Froude Number, and the timing of each kind of condition. Plant species normally inundated for three months in the wet season, for instance, could not survive if the same length inundation occurred in the dry season instead, and so timing is as important as the hydraulic condition itself. The links with hydrology now become clear:

- hydrological data detail the *magnitude*, *frequency*, *duration* and *timing* of each kind of flow over days, seasons, years and decades
- hydraulics transforms this information into descriptors of the *water-related conditions experienced* by each species over days, seasons, years or decades as relevant– whether it be mayflies under the stones of the riverbed or a riparian tree high on the bank.

Creating an understanding in this way of the hydraulic habitat of different species or communities is the important first step in development of a predictive capacity of how flow change will result in ecosystem change. Changes in any of the above four attributes of a flow regime will trigger ecosystem responses that will be as mild or severe as the flow change. Being able to predict such changes is a vital part of scenario analysis that should be integral to any planned water-management action.

- Step 1 – ascertain the physical conditions in which specified important species occur and describe their physical (including hydraulic) habitats
- Step 2 – use hydrological, hydraulic and, if available, geomorphological/sediment models to predict in scenarios how any planned water-resource management strategy could change physical conditions in the river
- Step 3 – link the model outputs to the known physical-habitat data on the selected species (Step 1), to predict how the species will change in abundance under each scenario.
- Step 4 – the vital next step, not dealt with in this report, is defining the economic, socio-economic and social implications for human society of these changes in the river ecosystem (King and McCartney, 2007).

To enhance their ability to play meaningful roles in such scenario analysis, many South African river ecologists, over the last two decades, have focused strongly on developing a better understanding of:

- the nature of river channels, in terms of the physical habitat they offer (Chapter 2)
- the nature of flow regimes, in terms of their ecologically relevant summary statistics (Chapter 3)
- the nature of flow types, as a visual expression of the hydraulic conditions experienced by aquatic plants and animals (Table 2.3)
- the various ways of describing hydraulic habitat, including Habitat Suitability Criteria (HSC), Flow Classes, and Hydraulic Biotopes (Chapter 4)
- Flow duration curves, and their links to channel cross-sections to display the magnitude of

discharge that inundates different bank vegetation communities

- and more.

Ecologists gradually came to understand and articulate that they needed information at higher resolutions than might be needed for traditional hydrological and hydraulic studies:

- daily rather than monthly average discharges, because monthly averages do not describe the day-to-day conditions faced by the biota
- instantaneous discharges on occasion, to ascertain, for instance, a flood peak or a maximum condition experienced by the biota
- high-resolution, low-flow hydraulic modeling, as opposed to the traditional flood hydraulic modeling, because the dry season or artificially created low flows are often a time of great stress for the biota and accurate descriptions of the conditions likely to be faced will enhance the accuracy of predictions of potential ecosystem change
- 2-D hydraulic modeling of the mosaic of conditions at a site rather than cross-sectional averages, to link with species' locations.

At the beginning of the project reported on in this document, the ecologists in the team listed areas in their studies of hydraulic habitat where they needed support from hydraulicians (Table 5-1). Essentially, two main areas of input from hydraulicians are needed:

1) *The descriptions/predictions of hydraulic habitat*. These will link with ecological data on species' hydraulic habitat, to jointly provide descriptions/predictions of how much habitat is available per studied species under various flow regimes
2) *The hydraulic data that ecologists should collect*. These data would complement that collected by hydraulicians for ecohydraulic studies.

Three key linkages between river ecology and hydraulics are discussed further in the following section.

Table 5-1 Areas of ecological concern in river studies and management that need hydraulic inputs

ECOLOGICAL CONCERNS	REQUIRED HYDRAULIC SUPPORT	FURTHER COMMENT
Maintenance of geomorphological features		
Channel maintenance – the fundamental physical habitat available for riverine life forms	The size and duration of flows that maintain the size and nature of the channel	Reduced flooding can lead to channel encroachment by vegetation, thereby reducing future channel capacity
Maintenance of multiple channels	The size and duration of flows that maintain areas of multiple channels	Braided and anastomosing channels offer a range of inundation and habitat conditions, thereby enhancing biodiversity
Maintenance of pools	The size and duration of flows that maintain pools in river beds	Pools are important refugia, especially for fish in times of low flow
Movement and sorting of bed particles	The size of flows that move different sized particles Which flows are most important for sorting bed particles by size?	Bed movement acts as a disturbance to aquatic life; sorting of bed particles by size enhances physical diversity of the river bed leading to enhanced biological diversity
Sediment erosion, transport and deposition	The size of flows and other relevant factors that affect the erosion, transport and deposition of sediments	Movement of sediments is a vital factor in dictating the nature of available physical habitat and thus which species can be supported
Bank erosion and stability	What are the main hydraulic factors affecting bank stability and how can change be predicted?	Sudden drops in flow can cause collapse of sodden banks
Formation and maintenance of in-channel exposed features.	Flows that create, maintain and erode in-channel features such as sandbars, gravel bars, islands and riffles	Riffles are highly productive areas that can be severely impacted by embeddedness (deposition of fines among the cobbles) if flows are reduced or sediment loads increased
The location and maintenance of pools in ephemeral rivers	What geomorphological, hydrological and hydraulic conditions dictate the location, size and pools in rivers that periodically have no surface flow?	Pools are vital survival features for wildlife and riverine biotas in a dry landscape
Maintenance of floodplains	The discharge at any point along a river that floods over banks The area, depth and duration of inundation resulting from any overbank flow	The relationship between flow magnitude and duration as an indicator of floodplain conditions has been used to link different kinds of flood years with size of fish catches (MRC 2006)
Depth and velocity conditions		
Stage-discharge relationship	The water depth or inundation height reached by any specified discharge, or alternatively the discharge required to reach and inundate any specified river feature. Resolution 1 m and less	Linked to the hydrological record this relationship defines for a site when any specified plant or animal species is normally in or out of the water, allowing life-cycle requirements to be ascertained?
Depth and velocity	What is the site-specific mosaic of depths and velocities at a specified discharge and how does it change under a time-series of discharges Resolution 0.5 m?	Velocity can be measured at the surface, 0.6-depth or near-bed; different locations of measurement are relevant for different species. The distribution of depth, velocity and other indicators of flow forces over the 2-dimensional stream bed is of greatest interest?

ECOLOGICAL CONCERNS	REQUIRED HYDRAULIC SUPPORT	FURTHER COMMENT
Microhabitats and the hyporheos		
Habitat within the river bed	How and under what conditions water moves through the interstitial spaces in the river bed? ; How it can be measured?	Water flushes clean interstitial spaces, allowing access to animals and oxygenation of these sub-surface areas
Hydraulics of groundwater	How does water move into and out of groundwater? How can the influence of groundwater on non-perennial rivers be studied?	Fluxes of water into the groundwater, and vice versa are considered to be important for productivity; knowing the hydrological conditions under which this movement occurs will assist with understanding stream functioning. Non-perennial rivers are thought to have far closer and more critical links to groundwater than perennial rivers, but the nature of these links remains obscure despite their importance for sustaining these ecosystems
The study of biofilms	What are the hydraulic conditions on the surface of riverbed rocks? How can these be measured in an ecologically relevant way?	Biofilms – communities of aquatic algae and other micro-organisms on riverbed rocks – are important food sources for fish and invertebrates, and indicators of nutrient conditions
Hydraulic descriptors		
Stream power, Froude Number, Reynolds Number and Shear Stress are hydraulic descriptors – how useful are they for ecological studies	In simple, ecologically relevant terms, what does each descriptor mean, how should it be measured and when is it valid to use it?	Which is best suited for describing; • the forces that shape physical habitat • species' hydraulic habitat • the forces acting on surface dwelling fauna at elevated discharges
Flow types – visual descriptors of complex hydraulic conditions (Table 2.3)	What is the hydraulic nature of flow types? Can individual flow types be characterised by data on water depth, current speed and substratum particle size?	Mapping visually-identified flow types is an easy and intuitively-understandable way for ecologists to capture the hydraulic complexity of a study site
Hydraulic modeling		
Use of hydrodynamic models to describe hydraulic habitat	Given a range of discharges how will the availability and distribution of hydraulic habitat conditions (depth and velocity) change across a study site?	See Step 2 above
Hydraulic link to response curves of organisms	How can these depth and velocity conditions in channels be changed into indices of habitat for aquatic organisms?	See Step 3 above

5.3 Key linkages between river ecology and hydraulics

5.3.1 Velocity and depth

River organisms respond not only to water depth and the total wetted surface area, but also to the forces that result from the water being in motion. Insights are needed on what is happening in terms of the range of depths and velocities available in the wetted channel over space and time, a need that requires sophisticated modeling techniques and detailed measurements for calibration.

One-dimensional (1-D) deterministic hydraulic models can predict a maximum and mean depth and velocity at a cross-section. These provide an indication of flows that would allow fish passage, for instance, or result in a cobble riffle drying out. A description of average conditions, however, conveys little about the modal ranges and therefore what proportion of a particular habitat for a species or guild would be lost at any given discharge. Nor does it provide information on the spatial distribution of different conditions, which is a major criticism of many hydraulic modeling approaches (Pollard, 2000) because the natural spatial variability and mosaic-like character of habitat in a river are critically important for maintaining levels of biological diversity.

One of the appeals of the Hydraulic Biotope Concept for ecologists (Section 4.4.3) is that habitats are represented in a spatial context that could then link to the observed distribution of organisms within a river reach, for given discharge values. 1-D hydraulic models are not able to capture the spatial relations between habitat classes. Two-dimensional (2-D) hydraulic models are not only able to predict the distribution, but also the location of point depth and velocity values across the modelled reach. Because of this they are able to represent the heterogeneity of conditions in river channels more accurately and at much higher resolutions than 1-D models. As they are spatially explicit, ecologists can use 2-D models to estimate measures of habitat heterogeneity (Bovee 1996), query the juxtaposition of different habitat types, and incorporate behaviour-based decision rules (Hardy *et al*. 2006).

A more useful output is a summary of the relative proportions of different classes of depth and velocity such as can be provided by empirical frequency distribution models (Lamouroux et al.,1998). This outlines the relative proportions contributed by each depth and velocity class interval, and allows a more confident prediction of the impact of loss of a key velocity or depth interval.

The spatial capabilities of 2-D models are particularly valuable when it comes to investigating cycles of wetting and drying on river floodplains. The models can be used to predict for any discharge not only the extent of floodplain inundation but also which key habitats will become flooded and which secondary channels will begin flowing. Their biological relevance can be interrogated by plotting the location of individual organisms on the model and querying the correlations between these observed locations and the values for habitat quality as predicted by the model (e.g. Guay, *et al.,* 2000; Paxton and King, in press) and the surface area of key habitats can be calculated.

5.3.2 Sediment movement and sorting

River flow acts on organisms either directly – through forces of shear and drag – or indirectly, by transporting, depositing or sorting the sediments on or in which they live. These sediments in the river's bed and its banks also form an important component of river habitat.

Different magnitudes of flow perform different types of work on the channel; eroding, transporting and sorting bed sediments, scouring fine material from between larger bed particles, eroding banks, or building sandbars. A key challenge for ecohydraulics is to identify which flows perform these different functions and what would happen if these flows were altered or removed by water-resource developments such as dams. It is thought, for instance, that:

- floods with return periods of about 1-in-2 years are dominant in maintaining the channel although the return period may be longer in ephemeral rivers
- the largest intra-annual floods are most important in sorting river-bed particles by size
- large intra-annual floods and inter-annual floods initiate bed movement, depending on bed roughness and particle size
- smaller intra-annual floods are important for scouring finer sediments

The transport of fines in the water column during floods provides an additional source of natural disturbance to invertebrate and algal populations.

5.3.3 Change through time: the habitat time series

Hydraulic approaches to river management should recognise the dynamic nature of river flow and the role that hydrological variability plays in structuring river communities (Orth, 1987; Capra *et al.* 1995; Heggenes, 1996; Hardy, 1998). Ideally, hydraulic studies should integrate some form of habitat time-series analysis because the size of a plant or animal population at any given time depends not only on immediate habitat availability but also on its past availability (Orth, 1987; Stalnaker *et al.,* 1989). Thus, the duration, frequency and timing of flows, and the time series of ensuing hydraulic conditions, should be an essential component of any assessment of biotic responses to flow change (Bain *et al*., 1988; Jowett and Duncan, 1990; Poff and Allan, 1995: Bonvechio and Allen, 2005). Knowing the length of time a riffle will be dry, for instance, or a floodplain inundated, is a vital prerequisite for the ecologist attempting to predict the impact on a river ecosystem of a management-driven flow change. An appropriate way of addressing these issues is to examine a habitat time series that involves translating a flow hydrograph into an index of habitat suitability for key species. In support of sustainable development and management of river systems, this should become a standard part of scenario analysis.

5.4 Conclusion

Some of the ecological needs for hydraulic information (Table 5-1) are being met to a large extent, whilst others have not been addressed in any form yet. The most comprehensive inputs have been linked to maintenance of channel features and river depth-velocity relationships, with growing activity in the field of ecohydraulic modeling and hydraulic descriptors. Areas receiving little or no attention as yet are microhabitats and the hyporheos.

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PART III : ECOHYDRAULICS IN PRACTICE

6. HYDRAULICS IN RIVER ECOSYSTEMS

CS James

6.1 Introduction

The purpose of environmental river hydraulics is to describe and predict the hydraulic conditions that influence the physical, chemical and biological nature of rivers in order to advance understanding of their ecological functioning and to inform management decisions regarding river conservation and rehabilitation. This requires firstly, establishing which hydraulic variables can best be related to physical and biological processes, and secondly, describing and predicting the occurrence of these variables so that the necessary associations with ecological processes can be made.

The chapters in Part II have provided descriptions of some of the associations between geomorphological and biotic features of rivers and the occurrence of water; Table 5.1 lists some particular ecological concerns and the roles of hydraulics in addressing them. This chapter presents some general guidance for selecting appropriate variables and models for providing hydraulic input, and the other chapters in Part III provide more detailed techniques for particular applications. Chapter 7 presents ways of describing flow resistance in rivers – an essential input to deterministic hydraulic modeling at all levels of resolution. Chapter 8 identifies hydraulic characteristics associated with channel form and substrate condition, and provides techniques for estimating maintenance flows. Chapter 9 presents current best practice for carrying out the hydraulic analyses necessary for determining the Ecological Reserve for rivers in South Africa. Chapter 10 describes some engineering measures for river rehabilitation and impact mitigation of river structures, including the provision of fishways and dam outlet structures.

6.2 Linking water occurrence and ecological functioning

Identifying appropriate hydrological/hydraulic variables and selecting models for predicting their occurrence must be based on an understanding of the occurrence of water within the system and its linkages with ecological functioning. This section describes the role of water in driving river ecosystems as a basis for relating hydraulic characteristics to physical and biological functioning, and the following section provides an overview of available hydraulic modeling strategies.

6.2.1 Water in the river ecosystem

The occurrence of water in a river originates with the input of precipitation, P, (varying in space and time) to a catchment system, producing streamflow (discharge), Q, in river channels as output, also varying in space and time (Figure 6.1) (James, 2008). The input of streamflow to a channel reach produces time-varying hydraulic conditions, H, at particular locations or sites. Together with other physical and chemical attributes, these hydraulic conditions constitute the habitat characteristics for riverine biota (as described in Chapter 4). The processes underlying the hydraulic conditions in a river channel are complex: the hydraulic conditions are determined by the discharge, the channel form and instream vegetation; the channel form is itself determined by the hydraulic conditions and instream vegetation, as well as the local geology and sediment supply; the occurrence of instream vegetation is determined in turn by the habitat defined by the channel form and the hydraulic conditions (James *et al.*, 2001). There is therefore a strong interactive, mutual feedback relationship between vegetation, hydraulics and channel form in river function that takes place over a range of spatial and temporal scales. The spatial dimension associated with water occurrence represents a catchment-scale areal extent for precipitation, a river reach scale distance for streamflow, and a local site or cross-section scale for hydraulics. The input-output transformations at any level within the system involve the movement of water through a physical template, which can be described by appropriate models. Of particular interest here are models relating habitat-relevant local hydraulic conditions to discharge.

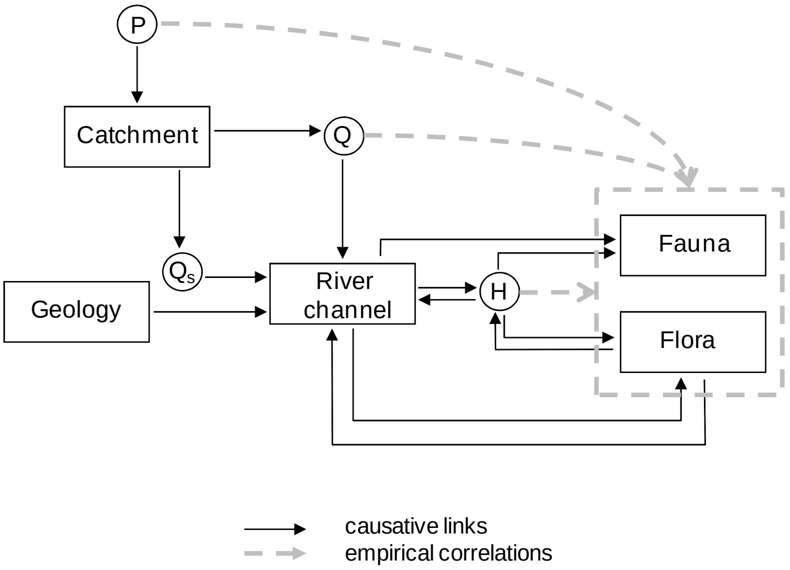


Figure 6-1 Linkages within the ecohydrological system (after James, 2008)

The occurrence of water at any level in the process description of Figure 6.1 is characterized by a nominal variable (e.g. rainfall, discharge, velocity, flow depth), its magnitude (implying its dimensions and units), its spatial characteristics (areal extent and spatial variation) as well as its temporal character (duration and temporal variation) (Figure 6.2). The spatial and temporal characteristics can apply over a wide range of scales; the temporal distribution of discharge in a river can be described during a flood event, over a season, from year to year or in decadal cycles, for example. Hydrological (including hydraulic), geomorphological and ecological processes operate at all scales and all levels of organization, and correct identification of variable scale is an important prerequisite for model selection.

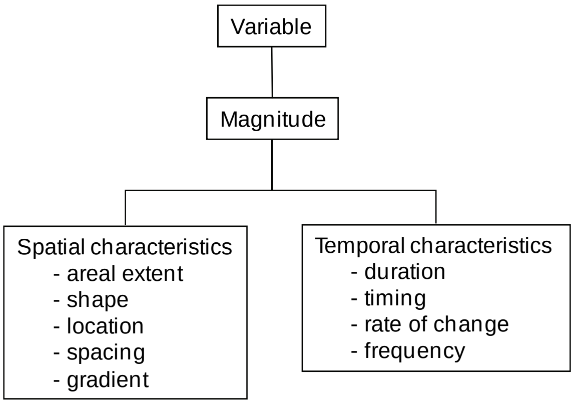


Figure 6-2 Attributes of hydrological/hydraulic variables (James, 2008)

6.2.2 Selecting linkages and defining variables

Riverine flora and fauna respond directly to local hydraulic conditions and only indirectly to streamflow and precipitation. However, it is sometimes desirable to relate ecological processes to higher level hydrological variables rather than attempting to elucidate the complete causative linkages (James and Thoms, submitted). The final, useful link of water occurrence with ecological structures and functioning will invariably be made by descriptive correlation (rather than causal explanation), whatever the level of the linkage. Biotic responses can be empirically correlated with the occurrence of water at any of the levels indicated in Figure 6.1, i.e. with precipitation, discharge or local hydraulics, depending on the issue at hand and the information available. For example, the incidence and prevalence of malaria in a region might be reliably and expediently correlated directly with seasonal rainfall, rather than attempting to describe all the processes linking rainfall events to the distribution of stagnant water in a complex landscape and its linkage to the life stages of mosquitoes. The life cycles of many aquatic and riparian species can be correlated with the temporal characteristics of river flow, without specification of flow velocities or water levels. At the lowest and immediate level, fish and invertebrate habitats are commonly defined in terms of the local hydraulic variables of flow depth and velocity (Chapter 4).

(A similar argument can be made for linking geomorphic responses to river flow: although large scale channel form is ultimately the consequence of the movement of individual sediment grains by local hydraulic forces, it is common practice to correlate reach and cross-section characteristics of alluvial rivers empirically with a characteristic discharge; flushing flows, on the other hand, are determined from relationships between grain characteristics and critical local hydraulic conditions (Chapter 8).)

Before selecting a model for relating ecological function to river flows, it is therefore necessary to decide on the level at which the water occurrence-biological function correlation should be made, and to specify the appropriate input and output variables and their temporal and spatial characteristics.

The appropriate linkage level is largely a matter of expedience, depending on its purpose and the type and amount of information available, but the level selected does have implications for the realism of the linkage description. The causative meaning and generality of correlations between flow descriptors and ecological characteristics weaken in ascending order as lumping and empirical relationships increasingly subsume rational explanation. The lower the level at which the empirical correlation between water occurrence and ecological process is made, the richer in explanation will be the ultimate linkage. High resolution description and modeling is not always practical or necessary, however, and has significant resource demands.

Two general approaches are in common use for defining the river flows required for ecological functioning. These make the water-biota linkage at the streamflow level (the hydro-ecological approach) and the local hydraulic level (the ecohydraulic approach). The hydro-ecological approach of correlating biotic response with streamflow, in terms of its magnitude and temporal characteristics (see Figure 6.2), is epitomized by the Natural Flow Regime concept proposed by Poff *et al*. (1997). This has led to widespread acceptance of streamflow as the ‘master variable’ governing ecological functions and processes, as discussed in Section 5.1. This is a useful concept because the flow regime presents the primary and immediate contextual variable for the occurrence of water in the river (James and Thoms, submitted). It provides a common context for the various hydraulic characteristics defining requirements for different species and communities, making it an appropriate variable for a whole ecosystem – as opposed to individual species – management. It is also useful because it is the water-related variable that is most amenable to management – it is in terms of discharge that environmental water requirements are specified, and in terms of discharge that they are effected by reservoir releases or control of run-of-river abstractions.

Direct correlation of biotic response with streamflow is appropriate when the temporal characteristics are more significant than the spatial ones, because temporal descriptors are essentially the same for variables at the different levels – frequency, duration, timing and rate of change are similar for discharge and the local hydraulic conditions it produces, such as flow depth and velocity (there are attenuations and delays, but these do not change the fundamental character of the necessary descriptors). It is therefore effective and useful to correlate the temporal character of discharge with the inundation tolerance and requirements of plants or the spawning of fish, even if the organisms are actually responding to flow depth or velocity. In such cases, the magnitude of the relevant hydraulic variable is usually not required explicitly, and its implicitness in the discharge for the particular river is sufficient. If magnitudes of local hydraulic conditions or their spatial variations are important, however, direct correlation with discharge is ineffective and the hydraulic variables produced by a specified discharge need to be quantified. So while spawning signals for fish may be effectively related to temporal variations of discharge magnitude, the local conditions required for laying eggs are determined by depth and velocity magnitudes and their spatial occurrence, as are other functions and activities described in Chapter 3.

Another shortcoming of the streamflow linkage is its lack of transferability – the same discharge will produce different local hydraulic conditions in different channel morphologies, whether these are at different locations in a river or associated with changed conditions at a particular location. River habitat rehabilitation is often implemented by artificially engineering the channel form, and different channel forms require different discharges to produce the same hydraulic conditions. Similarly, local hydraulic conditions for the same discharge could be different before and after a large channel re-forming flood (see Box 6.1).

The more fundamental linkage made in the ecohydraulic approach makes it more general than the hydroecological approach, and it is followed wherever possible in Ecological Reserve determinations in South Africa (Chapter 9). It is, however, more computationally demanding and resource intensive because the translation of discharge into local hydraulic habitat conditions is site-specific.

Box 6.1

The effect of channel form on hydraulic habitat – the Olifants River

1998

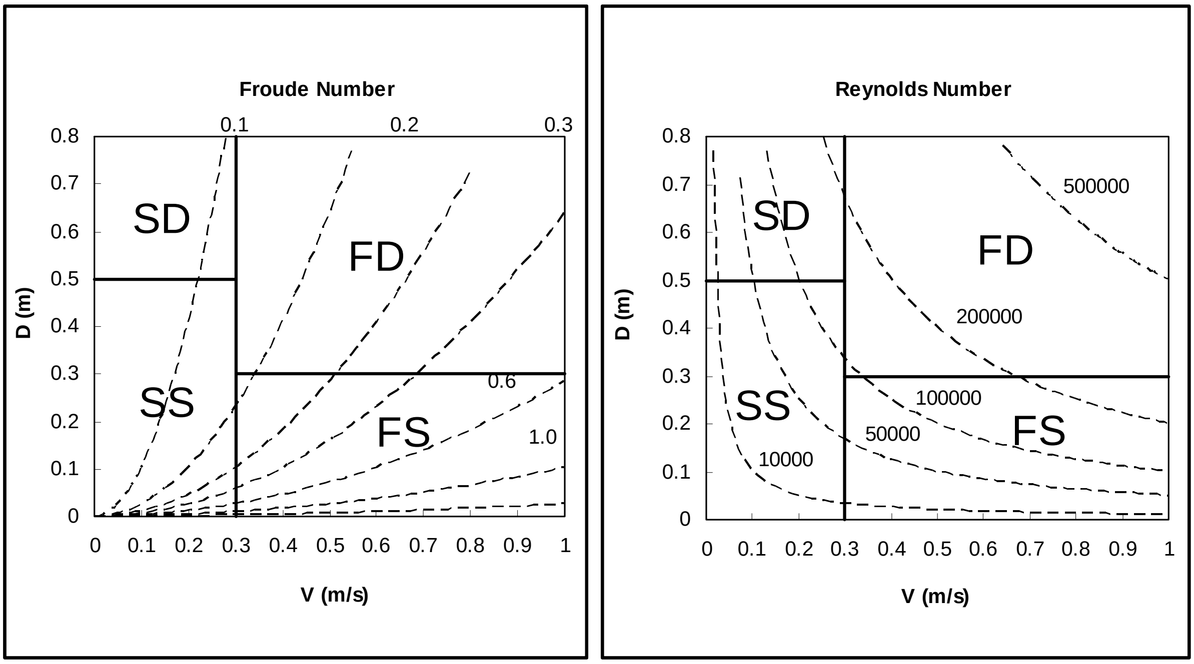
2004

The Olifants River in the Kruger National Park experienced a major channel-forming flood event in 2000. The photographs of a certain reach taken before and after the flood show the morphological change caused by this event. It is clear that the same discharge would produce very different hydraulic conditions in the pre- and post-flood channel forms. While an environmental flow regime established before the flood might provide the correct temporal cues for fish migration or spawning afterwards, the implied hydraulic habitat conditions would be grossly misrepresented.

If correlations are to be made at the hydraulic level, then it is necessary to specify the actual hydraulic variable/s to be used (e.g. depth, velocity, turbulence characteristics), the dimensions and resolution at which they should be described (e.g. velocity as a cross-section average, a distributed depth average or a full three-dimensional description), and what spatial and temporal characteristics are necessary (as defined in Figure 6.2). For physical processes, channel form is commonly correlated with a discharge magnitude with an associated temporal frequency, while substrate condition is related to a local shear stress or stream power (Chapter 8). Fish and macro-invertebrate habitats are characterized by depth and velocity with their spatial extent, location and arrangement characteristics (Chapter 4). It has been suggested (Table 5.1) that some classical non-dimensional hydraulic parameters representing combinations of velocity and flow depth, such as the Froude (*Fr*) and Reynolds (*Re*) numbers are useful representations of habitat condition. This notion should be applied with extreme caution; because they are dimensionless, the same values of these parameters can characterize flow conditions over a wide range of scales – the same values of Froude number could be associated with flows in a kitchen sink and the Amazon River, for example. Any observed correlations of *Fr* or *Re* with biotic function therefore have an implicit scale connotation (that of the river where the data were collected) and the results are not transferable to different channel sizes (see Box 6.2).

Box 6.2

Comparison of flow class and dimensionless hydraulic parameter characterization of hydraulic habitat



Velocity–depth classes provide a representation of habitat conditions, such as those formulated for fish in South Africa by Kleynhans (1999) (Section 4.6.6, Section 9.3.5). These can be represented graphically as spaces in a Cartesian plot of flow depth (*D*) against velocity (*V*) (Jordanova *et al.*, 2004); Figure 4.3). Contours of equal values of Froude number (*Fr*) and Reynolds number (*Re*) have been overlain on the Kleynhans (1999) flow classes in the above diagrams. These show that some classes include wide ranges of values of *Fr* and *Re*, and that some values of *Fr* and *Re* are represented over several classes. Unless associated with a particular scale, these dimensionless parameters may therefore give misleading indications of habitat suitability.

The variable specifications suggested above are suitable for some of the ecological concerns listed in Table 5.1, but not all; selection of appropriate variables depends on the nature of the dependence of the particular geomorphological or biological entity on water and the scale of interaction. Dollar *et al.* (2007) proposed a framework for associating the geomorphological, hydrological and ecological components of river ecosystems that can be used for identifying appropriate variables. The framework is founded on hierarchical concepts for relating complex structure to function and elucidating linkages.

A hierarchy is a graded organizational structure in which an entity at one level is a discrete unit of the level above and an agglomeration of units in the level below (Figure 6.3). Processes at any level are constrained by higher level structure and influenced by the functioning of lower levels. The levels are purely organizational and scale-independent, but can be characterized by spatial and temporal scales that define dimensions in terms of grain (indicating the resolution of its description) and extent (indicating the whole area or duration of influence). The framework of Dollar *et al.* (2007) defines organizational hierarchies for the primary disciplinary river sub-systems, i.e. the geomorphological, hydrological (including hydraulics) and ecological. These are then associated by scale in relation to the issue under consideration, enabling the relevant process interactions to be identified and described.

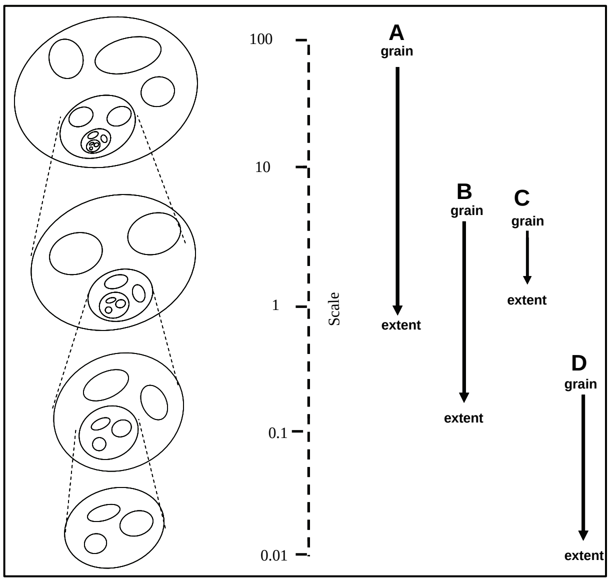


Figure 6-3 Hierarchical organization and associations with scale (Dollar *et al.*, 2007)

The organizational hierarchies for the three sub-systems are shown in Figure 6.4. The geomorphological hierarchy is consistent with most fluvial classification schemes (e.g. Frissel *et al.*, 1986), and the ecological hierarchy is well-established (Barrett *et al.*, 1997) (see Box 3.1). The hydrological hierarchy orders the occurrence of water from mere presence at the highest level, followed in increasing resolution at lower levels by quantity, rates of transfer between hydrological storages, then vectorial movement, and down to turbulence. (The 'hydrological' descriptors include hydraulic characteristics as well. The higher order descriptors (occurrence down to discharge) are hydrological in the sense of describing the spatial and temporal distribution of water, while the lower order ones are hydraulic in the sense of describing the behaviour of water.) All the levels are relevant for ecological interpretation: floodplain vegetation may depend simply on the wet/dry occurrence of water and its temporal characteristics, irrespective of the magnitude of discharge, velocity or flow depth; amounts of water are fundamental for the viability of pool and lake ecosystems; the dependence of biota on discharge and local hydraulics has already been discussed, and is the primary focus of this report. The hydraulic assemblage level includes combinations of local hydraulic conditions, such as described by surface flow types or biotopes (Chapter 4). It should be noted that the hierarchical order does not necessarily imply the only direction of causation, because different scale connotations are possible – the discharge in a river can provide the context for the full spectrum of descriptors, including water occurrence on floodplains down to turbulence around individual rocks.

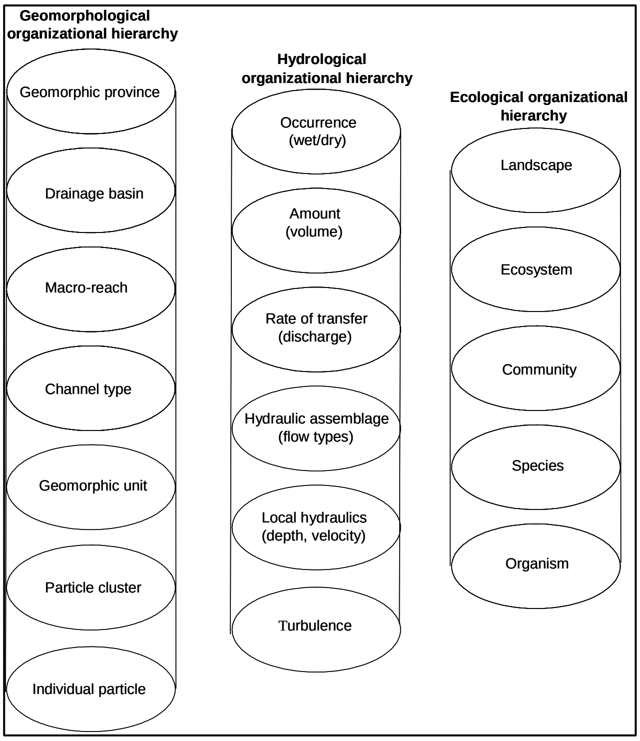
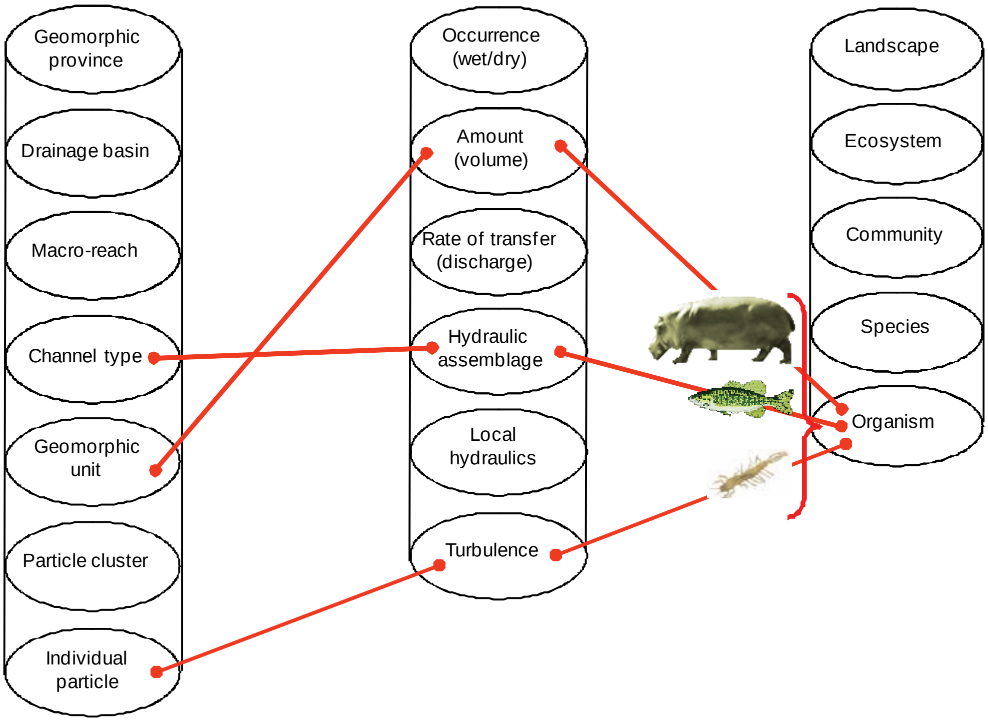


Figure 6-4 Geomorphological, hydrological and ecological organizational hierarchies (after Dollar et al.,2007)

The levels in the different hierarchies cannot be matched directly because they are not expressed in commensurate terms, and because they are scale-independent. For example, a mayfly nymph, a fish and a hippopotamus all belong to the same individual organism level in the ecological hierarchy, but because of their scale differences, their habitats are associated with descriptors at different levels in the geomorphological and hydrological hierarchies. Similarly, an individual particle in the geomorphological hierarchy could be a silt grain or a boulder which would respond to different hydraulic descriptors, and similar turbulence structures can occur around a single rock or a large island. Associating relevant components of the three sub-systems for resolution of a particular problem can only be done after scales have been assigned to the levels. For example, if the habitat requirements for a fish are to be specified, its size would set the scale for the entire ecological hierarchy; assignment of scale to the geomorphology of the river in question would indicate the level appropriate for fish requirements, and the two together would suggest appropriate hydrological descriptors. The appropriate time scale will become apparent after the relevant spatial scales are established.

Box 6.3

Establishing appropriate habitat hydraulic descriptors and formulating modeling strategies – an example of the influence of scale



A mayfly nymph, a fish and a hippopotamus all represent the same organizational level in the ecological hierarchy – all are organisms representing single species. Their hydraulic habitat requirements are obviously different, however, because of their different sizes, i.e. their implied spatial scales, and a different modeling strategy would be necessary for each. The scale associated with each organism will determine what geomorphological features and water descriptors should be associated with it: a hippopotamus will require an amount of water in a pool-type geomorphic unit; a fish's habitat may be defined in terms of ranges and distributions of flow depths and velocities over a channel type; a mayfly nymph may respond to turbulence around individual cobbles. These associations will indicate the descriptors for the physical environment and the occurrence of water within it that should be included in models for defining their flow requirements. For the hippopotamus, the only concern is the amount of water available at any time, which can probably be determined simply from a stage-discharge relationship for the pool and a weekly or monthly hydrological time series. The assemblage of flow depths and velocities constituting the fish habitat would require modeling to relate the occurrence of different values of these descriptors (and possibly their spatial arrangements) to a specified discharge. This would probably be required for establishing the lowest flows for a recommended regime, so the time variation of discharge would not be important and a steady hydraulic model would be appropriate, but a two-dimensional spatial description would be necessary. For the mayfly nymph, a three-dimensional description might be necessary to describe variations with depth as well as location.

Once an appropriate hydrological descriptor has been identified, its characteristics (Figure 6.2) and their scales relevant to the association to be described need to be specified. Flow depth and velocity are the most commonly used descriptors for making biological linkages, but they can be described at different scales and resolutions. For some problems (such as predicting the inundation of riparian vegetation) only a water level is required, while for others (such as for describing fish habitat) local flow depths and velocities may be necessary. The nature of the correlation to be made will then dictate how the flow depths and velocities should be described: for simple, broad correlations only cross-section average values may be necessary; quantification of the amount of habitat available requires descriptions of ranges of values over cross-sections or plan areas; ensuring connectivity or contiguity of different habitat types requires a description of the spatial arrangement of the variables. Habitat specification for macro-invertebrates may require complete three-dimensional descriptions of local values over area and depth. Selection of variable characteristics will, however, depend not only on the biotic dependencies but also on the information, models and resources available (see Section 6.3 and Chapter 9).

The example in Box 6.3 shows the use of the framework principles to establish the water descriptors most appropriate for defining the hydraulic habitat for different target species, and hence making correlations with their survival, growth and reproduction. The requirements to address other ecological concerns listed in Table 5.1 could be formulated by following similar logic. Selection of models for predicting the occurrence of selected descriptors is discussed in the following section.

6.3 Ecohydraulic Modeling

Once the appropriate descriptors of hydraulic habitat have been established, it is necessary to have knowledge of their occurrence in order for the correlations with biological functioning to be made. This knowledge may be obtained by direct measurement at the site of interest, or by prediction through modeling. Modeling requires knowledge of the occurrence of water at some higher, contextual level which must be transformed into the required descriptors by simulation of the intervening processes (Figure 6.1). For example, if the biological correlations are to be made with discharge, the contextual variable would be precipitation and the required streamflow time series would be obtained through hydrological modeling of the relevant catchment processes; if the correlations are to be made with local hydraulic conditions, then a historical or simulated streamflow record provides the contextual variable and hydraulic modeling is used. Most applications considered in this report are concerned with geomorphological and biological linkages made with hydraulic conditions and the magnitudes of discharges producing them. The primary modeling need is therefore for the transformation of discharge to local hydraulic conditions, particularly flow depth and velocity (the dependence of organisms on turbulence is poorly understood and is not addressed here). In practical applications the temporal attributes of water occurrence are conveyed by the discharge time series and the spatial attributes by the hydraulic variables.

Attention here is limited to cases of ‘simple’ response, i.e. situations not requiring consideration of the feedbacks between channel form, hydraulics and vegetation shown in Figure 6.1. This restriction is acceptable for the short-term description of hydraulic habitat for most animals, which are influenced by their environment but do not significantly modify it, but would not be for long-term prediction of interacting vegetation and sediment dynamics.

Depending on the application, descriptions of the occurrence of flow depth and velocity may be required at different levels of detail, as described in the previous section, i.e. cross-section averages, or distributions of depth-averaged velocities over cross sections or reach areas. Many different models and modeling approaches are available for predicting these characteristics under specified discharges. The main differences between them relate to the resolutions at which they describe hydraulic processes and their relative empirical and deterministic contents. An empirical model is based on a correlation of measured values of the variables of interest (water level and discharge, for example); a deterministic model is a causative description of the processes involved in the relationship between variables (such as the description of mass and momentum conservation by the Saint Venant equations for relating flow depth and velocity). Deterministic models always include some empirical content to account for particular system characteristics and the effects of underlying processes that influence the relationships between variables but are not explicitly described. This empirical content is introduced through equation coefficients (especially the resistance coefficient) and statistically up-scaled representations of smaller-scale processes (e.g. characteristic velocity profiles or eddy viscosity values resulting from turbulent momentum transfer). The higher the model resolution, the more realistic is the process description and the lower is the empirical content. This is not always an advantage, however, because high resolution models invariably require greater information input relating to system characteristics, especially topographical survey data. Empirical models, on the other hand require less system information but more flow information to provide the basis for variable correlation. A deterministic model will therefore be more general and have greater transferability, but an empirical model calibrated for a particular site will probably have greater accuracy (for example, a stage-discharge relationship derived from measured data will have less associated uncertainty than one generated by a deterministic flow model).

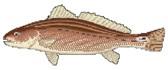
The most basic description of river hydraulics is the stage-discharge relationship at a particular site. This is best modelled by empirical correlation of measured data, as described in Section 9.3.4, requiring only measurements of water level and discharge and no physical description of the site. The stage-discharge relationship can also be determined deterministically, using the approaches described below; less flow data but more site information is then required. Cross-section average velocities require deterministic modeling, with some site survey information. The simplest approach, followed where site information is severely limited, is to assume uniform flow conditions. The appropriate hydraulic model is then a combination of the one-dimensional continuity equation with one of the resistance equations presented in Chapter 7, as explained in more detail in Section 9.3.4; information requirements are limited to the channel slope and cross section geometry and a resistance coefficient to account for the effects of the other channel characteristics. The distribution of cross-section average velocities along a river reach requires 1-D non-uniform flow modeling, such as by the model HEC-RAS (Warner *et al*., 2008); this requires similar information as a uniform flow model, but at a number of cross sections. The distribution of depth-averaged velocities across a section can be described approximately by considering the cross section as a number of adjacent, non-interacting sub-channels (e.g. as in HEC-RAS), but accurate description requires other modeling approaches. Hirschowitz and James (in press) present a purely empirical model for describing the variation of velocity away from emergent vegetation boundaries, requiring resistance calculations for the vegetated and unvegetated zones (Chapter 7) and the channel slope and cross-section geometry. More general description requires deterministic modeling that accounts for the transfer of momentum across the section, such as the Lateral Distribution Method, incorporated in the Conveyance Estimation System of HR Wallingford (2004); this requires basic resistance estimation and specification of channel geometry, as well as an eddy viscosity value. The distribution of depths and velocities over a two-dimensional area can also be modelled empirically or deterministically. Various frequency distributions describing the occurrence of depth and/or velocity over cross sections or reaches have been proposed (see Box 6.4); they are used in the HABFLO model described in Section 9.3.4. These typically require input in terms of some channel and flow characteristics. Such descriptions indicate the relative abundances of different habitat conditions, but not their spatial arrangement (analogously to a flow-duration relationship, which gives relative proportions of durations of discharge magnitudes over a time period without any indication of their timing or temporal distribution). Hydraulic biotopes or surface flow types (Chapter 4) provide qualitative ways of representing combinations of flow conditions as a basis for describing hydraulic habitat. Although popular with some ecologists, this approach may suffer from the same scale limitation as use of the Froude and Reynolds numbers in its hydraulic characterization, and the occurrence and change of biotope arrangement with varying discharge is difficult to predict without 2-D deterministic modeling (which might make the biotope description superfluous anyway). Deterministic 2-D modeling (e.g. River2D, Steffler and Blackburn, 2006) provides spatially explicit descriptions of flow depth and velocity, which can be interpreted in terms of abundance and spatial arrangement as necessary (see Box 6.4). These models require significant site survey information for input, however. The distribution of local velocity through the water column can be estimated empirically using vertical velocity distribution equations (e.g. the classic logarithmic distribution) which require at least flow depth and bed roughness as input. Accurate description of combined vertical and areal velocity distributions requires 3-D modeling, which is not often warranted and is not pursued in this report.

Deterministic 1-D and 2-D models can be used to describe both steady and unsteady flow. In most ecohydraulic applications, assuming the temporal variations to be similar to those of the governing discharge time series is sufficient, although unsteady modeling may be necessary for estimating boundary shear stresses in flushing flow determinations.

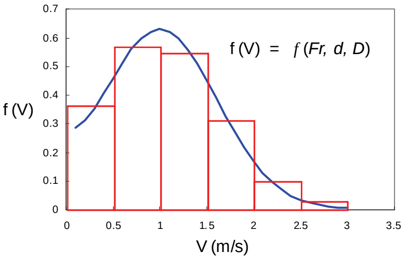
The different types of models are comprehensively reviewed by Hirschowitz *et al*. (2007), and their applications in Ecological Reserve determination are described in Chapter 9. Selection from the many models available, all with different advantages and shortcomings, requires consideration of the output requirements, the levels of accuracy and precision required and the resources of time, money, effort and information available (especially in relation to the level of Ecological Reserve determination being undertaken). It must be emphasized that a high resolution model (e.g. 2-D) is not necessarily better than a lower resolution (e.g. 1-D) one – it is meaningless to describe the hydraulic conditions at a higher resolution than the available Habitat Suitability Criteria can use, for example. The review of Hirschowitz *et al*. (2007) and practical experience in South Africa suggests that the HEC-RAS model (Warner *et al*., 2008) for 1-D analyses and River2D (Steffler and Blackburn, 2006) for 2-D analyses are adequate for most ecohydraulic applications; both may be downloaded from the internet free of charge. The quality of modeling output can only be as good as the input, and careful specification of resistance (Chapter 7) is important at all levels.

Box 6.4

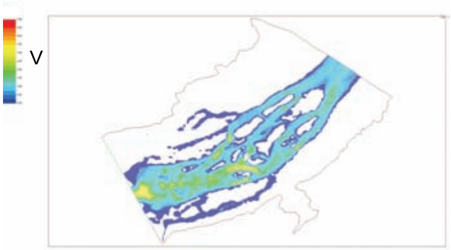
Empirical and deterministic modeling of hydraulic habitat



Empirical model



Deterministic model (2-D)



The availability of hydraulic habitat for a nominated fish species at a particular river site can be described through empirical or deterministic modeling. The empirical model is a statistically derived frequency distribution of velocity classes, derived from measured data at similar sites. The deterministic model is a 2-D simulation of flow by solution of the Saint Venant equations. The empirical model output describes the relative abundance of the different velocity classes, but not their spatial distribution. The deterministic model provides a spatially explicit description of velocity variation from which the relative abundance of classes could be derived, as well as measures of contiguity or fragmentation if required. The empirical model requires only coarse description of flow and bed characteristics and its accuracy depends on the representativeness of the data used for its compilation. The deterministic model is more general and could probably accommodate a wider range of discharge input, but it requires detailed topographical survey information for the site.

6.4 Conclusion

The associations of geomorphological and biological features and functioning with the occurrence of water in rivers, as identified and described in Part II, can be quantified and applied for conservation and management purposes through hydraulic modeling. Planning an appropriate modeling strategy requires careful selection of variables for quantifying linkages, and choosing a type of model that involves the selected variables at relevant scales and resolutions and has realistic information requirements. Some of the ecological concerns listed in Table 5.1 are addressed directly in Part III, while others can be addressed through applications of the principles outlined in this chapter; some will require new developments. The success of ecohydraulic applications depends on both the reliability of the water-biota correlations and the ability to model the occurrence of the water descriptors. Current hydraulic modeling capabilities are probably adequate for making the necessary linkages with the current knowledge of the dependence of biota on hydraulic characteristics, as described in Chapter 9, although better resistance relationships for low flows and more representative velocity frequency distributions need to be developed. Improving the confidence of predictions probably depends more on gaining better understanding of biological responses than further development of hydraulic models.

6.5 References

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Notation

D: flow depth
Fr: Froude number
H: hydraulic conditions
P: precipitation
Q: discharge, streamflow
Re: Reynolds number
V: flow velocity

7. FLOW RESISTANCE IN RIVERS

CS James

7.1 Introduction

One of the central problems in river ecohydraulics is the determination of flow depths and velocities corresponding to specified discharges. The depths and velocities result from interactions between the flow and the channel boundaries, which take place over a range of spatial scales, and the net effect of the processes induced by these interactions reflects the 'resistance' of the channel.

The relationship between flow depth, velocity and discharge (and hence the resistance) can be described at different levels of resolution, depending on the purpose of the analysis, the amount and type of information available, and the ways in which the underlying processes can be accounted for. For some problems (such as predicting inundation of riparian vegetation) only a stage-discharge relationship is required, while for others (such as describing fish habitat) local flow depths may be required at cross-sections or over two-dimensional plan areas. Similarly, velocities may be required as representative reach values, cross-section averages, cross-section distributions of depth-averaged values, two-dimensional areal distributions of depth-averaged values, or even complete three-dimensional descriptions of local values over area and depth. These requirements indicate the appropriate type of predictive model to be used. In all cases, the model will describe processes at a certain level of resolution and account for the effects of processes at higher levels through empirical input, particularly by specification of a resistance coefficient. The verisimilitude of process modeling therefore increases with the resolution of modeling, while the empirical input becomes more process-specific and less 'lumped'. The variety of processes accounted for by lumped resistance coefficients is the main reason why different coefficient values are appropriate for 1-D, 2-D and 3-D models, even for the same river reach. For example, flow around a river bend involves complex 3-dimensional secondary circulation. If only cross-sectional average conditions are of interest, a 1-D model would be appropriate and the effect of secondary circulation on these would be accounted for by the resistance coefficient. If the spatial variation of local hydraulic conditions is required, a 3-D model would have to be used. Such a model would simulate the secondary circulation processes and the appropriate resistance coefficient would therefore only account for the effects of the finer scale processes, such as the surface resistance associated with the bed roughness. The value of resistance coefficient used must therefore be chosen to account for the processes that are not described explicitly by the model being used, i.e. the value to be specified depends on the model to be used as well as the characteristics of the river.

The appropriate resolution of modeling is not necessarily determined by its purpose only, however, but also by the feasibility of accounting for all relevant processes. For example, even if only a stage-discharge relationship is required, there may be important phenomena influencing effective resistance that require at least 2-D modeling, such as the interaction between main channel and flood plain flows in a compound channel.

The amount and detail of channel information required by different models increases with the resolution of their process descriptions, from just a longitudinal slope and a number of cross-section shapes at low resolutions to detailed reach topography at high resolutions. On the other hand, because of their more realistic process descriptions, high resolution models require less site-specific flow information for calibration than do low resolution models, and are more generally applicable and transferable. Low resolution modeling is therefore appropriate where flow data are plentiful and channel data are limited, while high resolution modeling is appropriate where flow data are limited and channel data are plentiful. Sufficient flow information may even obviate the necessity for deterministic modeling – the most reliable stage-discharge relationship at a section, for example, would be that obtained by statistical correlation of measured discharge and water level data; a reach resistance coefficient determined from sufficient measured flow data would be better than any attempted estimation from physical channel characteristics. Site-specific flow information of the type needed will always be more reliable than model predictions, and should be collected and used to the fullest extent possible.

The way flow resistance should be described and the value of the inevitable empirical resistance coefficient therefore depend on what processes are explicitly accounted for in the model used and which ones are to be accounted for by the coefficient. Selection and application of models and resistance formulations therefore require appreciation of the underlying causative processes within the context of the problem to be solved, and the information available or accessible. This chapter presents formulations appropriate for describing different resistance phenomena and guidance for estimating their corresponding coefficients.

7.2 Stage-discharge relationships derived from flow data

In cases where only the water levels corresponding to specified discharges are required (such as for defining inundation levels for riparian vegetation) and measured data are available, the best description of the stage-discharge relationship is obtained by direct correlation. In many cases, such as for Rapid level Reserve determinations, very few measurements are available and fitting a standard equation form to these is advisable. The recommended equation form is

$$y = aQ^b + c \tag{7.1}$$

in which y is the maximum flow depth in the cross-section (m), Q is the discharge (m^3/s) and c is the flow depth where flow ceases, i.e. the maximum depth of pooled water remaining on the cross-section when discharge is zero (m). A typical stage-discharge relationship determined in this way is shown in Figure 7.1.

Obviously the more data points there are, the more reliable will be the description of the relationship. If increased reliability is desired and additional flow data cannot be obtained, the relationship can be strengthened by applying resistance equations, as described in the following sections. This will require additional information to characterise the channel topography and roughness. The existing flow data should be used to estimate resistance coefficients, supported by the guidelines in the following sections. The derivation of stage-discharge relationships is dealt with in more detail in Chapter 9.

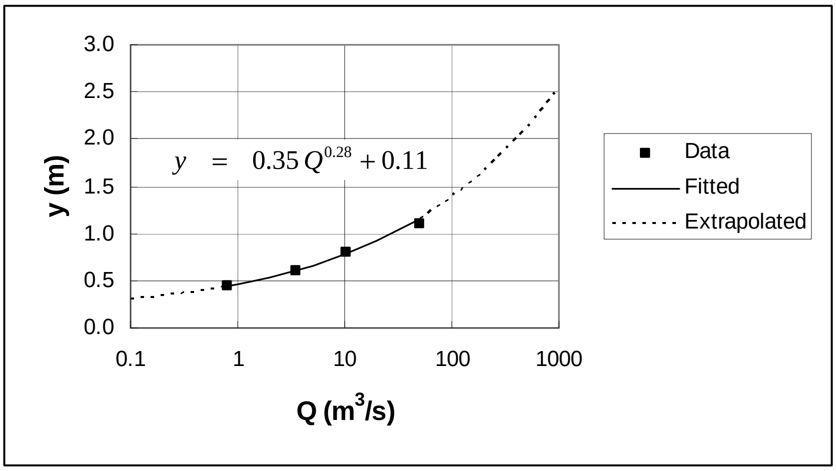

Figure 7-1 **Example of a stage-discharge relationship determined by correlation of field data**

7.3 Sources of flow resistance and their description

Origins of resistance can be recognised in features or phenomena that impose forces opposing the motion of the water and induce dissipation of energy. Their effects can be quantified by considering either the forces (momentum approach) or the energy losses (energy approach). The interpretation is often a matter of choice (e.g. the effect of a single large element on the flow can be described through analysis of the drag force it imposes or the energy dissipated by turbulence in its wake), and one or other may be easier for different effects. Yen (2002) has highlighted the dangers of confusing the interpretations and corresponding variables associated with the two approaches, but the distinctions are subtle for conditions of steady, uniform flow, which is the focus of attention here.

Different types of flow resistance have been recognised. The following classification proposed by Rouse (1965) and adopted by Yen (2002) is useful.

Surface resistance results from the shear stress at the boundary in contact with the flow, producing shear and associated viscous and turbulent energy dissipation through the flow.

Form resistance results from the unsymmetrical distribution of pressure and the dissipation of turbulent energy produced by flow separation around submerged or partially submerged boundary irregularities. This type also includes resistance associated with flow patterns induced by the channel form, such as secondary circulation around bends.

Wave resistance results from the distortion of the free surface by large features, which affects the pressure distribution and dissipates energy by wave motion.

Resistance associated with local acceleration or flow unsteadiness includes situations of local occurrences of critical flow and subsequent expansions (termed ‘spill resistance’ by Leopold *et al*., 1960), and flow instabilities (such as roll waves on steep slopes).

The physical characteristics of natural channels induce all of the above types of resistance. Surface resistance is always present, but may be dominated by other types in some situations. Form resistance is associated with channel irregularities ranging in scale from micro-roughness features such as pebble clusters, through alluvial bed forms to channel bars and pool-riffle sequences, as well as vegetation. Wave resistance is similar to and often associated with form resistance, and the two types may sometimes be treated together. Local acceleration and flow unsteadiness type resistance are relatively uncommon in the situations considered here, and where local acceleration occurs it will produce effects similar to form resistance and can therefore be accounted for in a similar way. The main types of resistance accounted for in the equations to be presented are therefore the surface and form types. Different types of resistance often occur in combination and accounting for them simultaneously is a significant challenge.

The following three equations are commonly used to describe the relationship between flow depth, velocity and channel characteristics, as governed by flow resistance.

Chézy:
$$V = C\sqrt{RS} \tag{7.2}$$

Darcy-Weisbach:
$$V = \sqrt{\frac{8g}{f}}\sqrt{RS} \tag{7.3}$$

Manning:
$$V = \frac{1}{n}R^{2/3}S^{1/2} \tag{7.4}$$

In these equations V is the cross-section average velocity (m/s), R is the hydraulic radius (m) (= A/P where A is the cross-sectional area (m^2) and P is the wetted perimeter (m)), and S is the energy gradient, which is equal to the channel gradient for steady, uniform flow. C (m$^{1/2}$/s), f and n (s/m$^{1/3}$) are the corresponding resistance coefficients.

The origins of these equations show that they were developed for, and are really only appropriate for describing surface resistance although they have commonly been used to account for other effects as well. Their forms are actually inappropriate for describing form resistance and their persistent use in form-dominated situations has led to much confusion in estimations of corresponding resistance coefficients. It is possible to distinguish between surface and form resistance, and this has been done particularly for flow through vegetation. James *et al.* (2008) propose a convenient equation form for emergent vegetation, but which would also be suitable for large discrete roughness elements in rivers, i.e.

$$V = \sqrt{\frac{1}{C_S + C_D}}\sqrt{2glS} \tag{7.5}$$

in which l is a roughness element concentration length (m) defined by

$$l = \frac{s^2}{d} \tag{7.6}$$

in which s is the average clear spacing between drag-inducing roughness elements (m^2) (which can also be expressed as $(1/N)^{0.5}$ where N is the number of elements per unit area), and d is the element frontal width (m). C_D is the element drag coefficient and C_S is the surface resistance coefficient, given by

$$C_S = \frac{f\,l}{4D} = \frac{2\,g\,l\,n^2}{D^{4/3}} \tag{7.7}$$

in which f and n are the Darcy-Weisbach and Manning resistance coefficients for the surface between the roughness elements, and D is the flow depth. In many situations the surface resistance component is negligible and equation (7.5) then reduces to a very simple form. Note that where form drag dominates, the average velocity does not depend on flow depth, as indicated by the conventional equations.

The use of the different resistance equations is often a matter of choice, and may be dictated by the input requirements of particular models. Equations (7.2) to (7.4) are essentially equivalent and coefficient values can be easily converted between them and also equation (7.5), using the following relationships.

$$C = \sqrt{\frac{8g}{f}} = \frac{R^{1/6}}{n} = \frac{R^{2/3}}{\sqrt{\dfrac{2\,g\,l}{C_S + C_D}}} \tag{7.8}$$

Despite this equivalence, historical developments and usage suggest that it is appropriate to reserve the Darcy-Weisbach f for very local values associated with surface resistance and Manning’s n for overall cross-sections or reaches where contributions to resistance from a variety of sources are accounted for. The Chézy equation is not widely used for rivers.

In the following sections the physical channel characteristics contributing to flow resistance are identified and appropriate equations and methods for estimating the corresponding resistance coefficients are presented.

7.4 Channel bed resistance

The effect of the channel bed is the primary consideration when evaluating the resistance in a river. It is important to distinguish between immobile bed and mobile bed conditions (Figure 7.2). All river beds move during sufficiently high flows and their movement has important ecological implications (as described in Section 3.2.3), but those consisting of gravels, cobbles or boulders may usually be considered to be immobile when assessing hydraulic habitat, while those with sand beds are mobile even under low flow conditions. The hydraulic conditions associated with bed movement are discussed in Chapter 6. Under both conditions the bed induces both surface and form resistance, but different treatments are required because the sizes of immobile roughness elements can be measured while mobile beds change form with flow condition, and predicting the form must be part of the analysis.

(a) (b)

Figure 7-2 Examples of immobile bed (a) and mobile bed (b) conditions

7.4.1 Immobile beds

The type of resistance presented by an immobile bed depends on the size of the substrate material (*k*) relative to the flow depth (*D*) (Figure 7.3). The condition of small-scale roughness occurs if the roughness elements are well submerged (D/k > ~10, although some authors suggest a limit of 4), and the resistance effect can then be treated as surface type. Large-scale roughness refers to the condition where the water surface is at or below the tops of the roughness elements ($D/k \leq$ ~1), and the resistance is almost entirely of the form type. Between these approximate limits is a transition through intermediate-scale roughness where both types contribute.

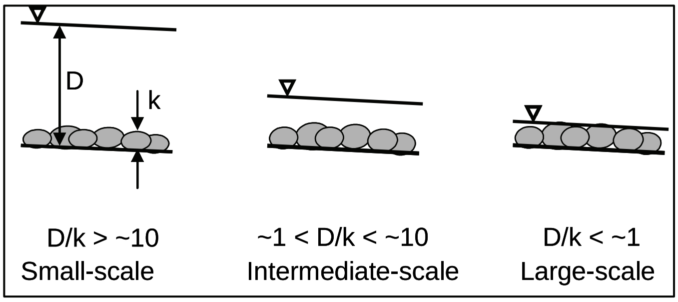

Figure 7-3 Scales of roughness for resistance definition

Resistance estimation approaches for these conditions are presented below.

Small-scale roughness

Any of the three common resistance equations (equations (7.2) to (7.4)) are appropriate for describing the small-scale roughness condition. The resistance coefficient depends on the characteristics of the bed substrate and the flow condition. Most results predict local (rather than reach) values and are expressed in terms of the Darcy-Weisbach *f*.

The value of *f* depends on whether the flow is laminar or turbulent as well as on the roughness of the boundary. Flow in river channels is rarely laminar and attention here is limited to turbulent flows. Three turbulent conditions need to be recognised, however, depending on the presence or absence of a viscous flow sub-layer near the bed and its thickness relative to the size of the surface roughness. Turbulent flow is hydraulically smooth if the viscous sub-layer completely submerges the roughness elements, transitional if it is about the same size and hydraulically rough if the roughness elements protrude through the viscous layer and break it up. These conditions can be characterised by the shear Reynolds number,

$$\mathrm{Re}^* = \frac{u_* k_s}{\nu} \tag{7.9}$$

where k_s is the Nikuradse roughness size (m), and u_* is the shear velocity (m/s),

$$u_* = \sqrt{\frac{\tau_0}{\rho}} = \sqrt{g R S} \tag{7.10}$$

where τ_o is the shear stress on the bed (N/m^2) and ρ is the water density (kg/m^3).

The shear Reynolds number can be used to define the regimes of turbulent flow, as follows.

$$\left.\begin{array}{ll} Re^* < 5 & \text{hydraulically smooth flow} \\ 5 < Re^* < 70 & \text{transitional flow} \\ Re^* > 70 & \text{hydraulically rough flow} \end{array}\right\} \tag{7.11}$$

Equation forms for f for each of these regimes have been proposed by the ASCE Task Force on Friction Factors in Open Channels (1963), i.e.

For hydraulically rough flow ($Re^* > 70$):

$$\frac{1}{\sqrt{f}} = c \log\left(a \frac{R}{k_s} \right) \tag{7.12}$$

For hydraulically smooth flow ($Re^* < 5$):

$$\frac{1}{\sqrt{f}} = c \log\left(Re \frac{\sqrt{f}}{b} \right) \tag{7.13}$$

For transitional flow ($5 < Re^* < 70$):

$$\frac{1}{\sqrt{f}} = -c \log\left(\frac{k_s}{a R} + \frac{b}{Re \sqrt{f}} \right) \tag{7.14}$$

Note that these equations are premised on the existence of a logarithmic distribution of velocity along a vertical profile through the flow depth. They should not be expected to be reliable and consistent under conditions where the velocity distribution is not logarithmic, such as where significant form resistance occurs.

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

$$\left.\begin{aligned} a &= 12 \\ b &= 2.51 \\ c &= 2 \end{aligned}\right\} \tag{7.15}$$

Values of k_s are well established for artificial, lined channels and are tabulated in many standard text books (e.g. Henderson, 1966; French, 1985). Flow in natural rivers is mostly hydraulically rough, and many variations of the form of equation (7.12) have been proposed. The greatest source of uncertainty in estimating f is the value of k_s selected. There is emerging consensus that a value of $3.5d_{84}$ is a realistic representation of k_s for gravel bed rivers (d_{84} is the size of bed particle for which 84% of particles are smaller). This is larger than the predominant physical roughness size, and appears to account also for the form resistance influence of bed microtopography that would not be easily distinguishable or accountable otherwise. Average values of a and c as calibrated by a number of researchers for gravel beds are 12.24 and 2.07 respectively. A workable equation for f is therefore

$$\frac{1}{\sqrt{f}} = 2.07 \log\left(\frac{12.24R}{3.5d_{84}}\right) \tag{7.16}$$

Equations for f have also been presented in the form of a power function, i.e.

$$\frac{1}{\sqrt{f}} = d\left(\frac{R}{k_s}\right)^e \tag{7.17}$$

Bray and Davar (1987) recommended $d = 1.9$ and $e = 0.25$ for $k_s = d_{84}$. For $k_s = 3.5d_{84}$, the equation can be written as

$$\frac{1}{\sqrt{f}} = 2.6\left(\frac{R}{3.5d_{84}}\right)^{0.25} \tag{7.18}$$

Although Manning's n can be determined from f through equation (7.8), equations have also been calibrated for predicting n directly from the bed grain size. Strickler (1923) proposed

$$n = \frac{k_s^{1/6}}{6.7\, g^{1/2}} \tag{7.19}$$

and there have been many other calibrations of the relationship $n = ck_s^{1/6}$, producing different values of the coefficient c, depending on the definition of k_s. Using the equivalence relationship of equation (7.8) and using $3.5d_{84}$ to represent k_s, equation (7.19) can be expressed in the form of equations (7.17) and (7.18) with d = 2.4 and e = 0.167.

Intermediate and large-scale roughness

As the flow depth reduces to approach the size of the bed roughness elements, the description of resistance as pure surface type becomes less satisfactory as the form drag on the roughness elements becomes more significant, and eventually dominates for large-scale roughness conditions. If the Darcy-Weisbach or Manning's equations are used through the full range of flow depths, the resistance coefficient values must be varied to account for the inappropriate process description of the equations where there is a form resistance contribution. The required value increases with decreasing *D/k* (and increasing form resistance) to a maximum at about *D*/*k* = 1. In natural rivers the change in *f* can be from less than 0.1 for the small-scale roughness condition to a maximum of more than 10. Figure 7.4 shows such a variation of *f* with *D/k* through the intermediate-scale roughness range for 114 mm hemispherical roughness elements in laboratory experiments undertaken by Jordanova and James (2007).

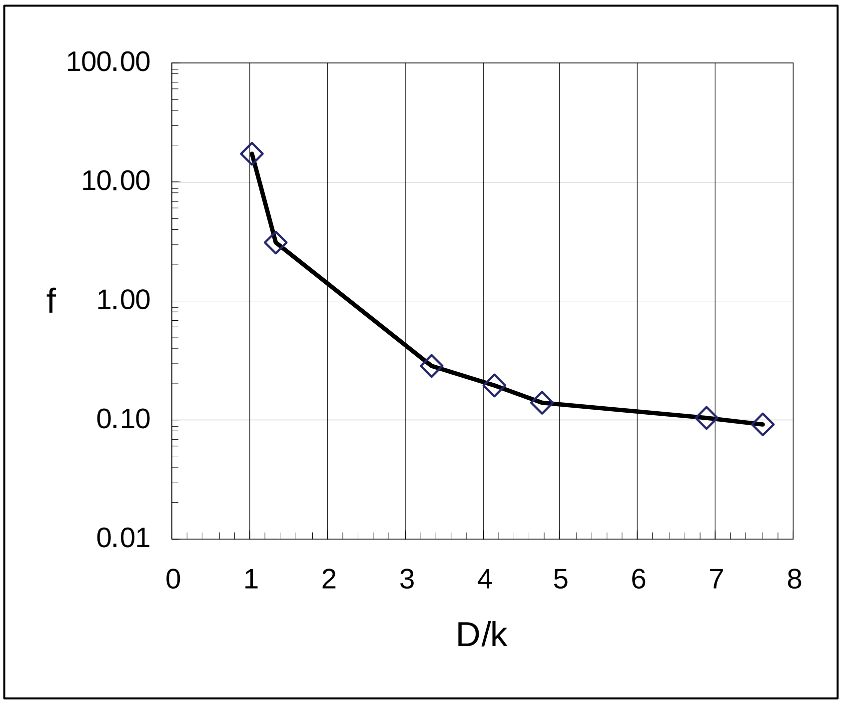

Figure 7-4 Variation of Darcy-Weisbach resistance coefficient in the intermediate-scale roughness zone (data from Jordanova and James, 2007)

Most results presented to date do not explicitly account for the different resistance phenomena. They assume the validity of surface resistance type equations and provide calibrations of the semi-logarithm or power functions for resistance coefficients using data that span the full scale spectrum. Bathurst (1985), for example used data with D/d_{84} ranging from 0.43 to 7.1 to produce

$$\sqrt{\frac{8}{f}} = 5.62\log\left(\frac{D}{d_{84}}\right) + 4 \tag{7.20}$$

which can be rewritten as

$$\frac{1}{\sqrt{f}} \quad = \quad 2.0 \log \left(\frac{18R}{3.5 d_{84}} \right) \tag{7.21}$$

Subsequently (Bathurst, 2002) he suggested a dependence of resistance on channel slope. From 27 sets of selected field data with $0.37 < D/d_{84} < 11.4$ he produced the following equations for different ranges of slope.

For $S < 0.008$

$$\sqrt{\frac{8}{f}} \quad = \quad 3.84 \left(\frac{D}{d_{84}} \right)^{0.547} \tag{7.22}$$

For $S > 0.008$

$$\sqrt{\frac{8}{f}} \quad = \quad 3.10 \left(\frac{D}{d_{84}} \right)^{0.93} \tag{7.23}$$

Because of the limitations of the Darcy-Weisbach equation under intermediate- and large-scale roughness conditions, these correlations for f should be used with caution in situations different from those corresponding to their data bases.

Lawrence (1997) explicitly acknowledged the different resistance phenomena in the three roughness zones. Although she persisted with the Darcy-Weisbach equation, she proposed a separate equation for the resistance coefficient in each zone. For the small-scale roughness condition she recommended an equation similar to equation (7.16). For intermediate-scale roughness she proposed

$$f \quad = \quad \frac{10}{\left(\frac{D}{k} \right)^2} \tag{7.24}$$

and for large-scale roughness

$$f \quad = \quad \frac{8}{\pi} P \, C_D \, MIN \left[\frac{\pi}{4}, \frac{D}{k} \right] \tag{7.25}$$

in which P is the proportion of the surface covered by the larger, drag-inducing particles, C_D is the drag coefficient of the particles and k is represented by d_{50}. The MIN term gives the projected area of a hemispherical particle, depending on whether the water surface is above or below the top of the particle.

The intermediate- and large-scale models of Lawrence (1997) have not been calibrated sufficiently for river scale situations (they were developed for very low overland flows where viscous effects might be significant). They do, however, predict the variation of f through the different scales of roughness realistically, and could provide a useful basis for site-specific calibration.

All of the formulations presented thus far for large- and intermediate-scale roughness conditions provide ways of estimating resistance coefficients for application of the Darcy-Weisbach surface-type resistance equation (equation (7.3)). This makes the implicit assumption that the drag forces on large roughness elements can be projected onto the bed and treated as an equivalent boundary shear stress, leading erroneously to a dependence of velocity on flow depth that must be compensated for by a varying resistance coefficient.

Jonker (2002) presented an equation for large-scale roughness conditions that ostensibly predicts velocity as independent of flow depth, i.e.

$$V \quad = \quad \sqrt{2\,g}\,\sqrt{\frac{d\,S}{C_x}} \tag{7.26}$$

in which d is the bed particle diameter (m) and C_x is a resistance coefficient. He calibrated C_x using published data for rivers in the Western Cape. In fact, the calibration is for the intermediate roughness range; it is based on data for relative roughness 0.61 < D/d_{50} < 4.8 but with only one data point for D/d_{50} < 1. This calibration gives

$$C_x \quad = \quad 0.5285\left(\frac{R}{d_{50}}\right)^{-2.166} \tag{7.27}$$

showing strong dependence on flow depth, which is correct for intermediate-scale roughness but not for large-scale roughness. Using the equivalence relationship of equation (7.8) and assuming $d_{84}/d_{50} = 1.9$ (a typical ratio for log-normally distributed sediments) equations (26) and (27) can be expressed in the same form as equations (7.17) and (7.18) with d = 0.482 and e = 0.583.

Jordanova and James (2007) accounted for the distinct contributions of form and shear resistance and their different influences under large-scale and intermediate-scale conditions. For large-scale roughness ($D/k < 1$) they propose

$$V \quad = \quad \sqrt{\frac{1}{C_D\,N\,A_p}}\,\sqrt{R_V}\,\sqrt{2\,g\,S} \tag{7.28}$$

in which C_D is the drag coefficient for the roughness elements, N is the number of roughness elements per unit bed area, A_p is the area of an element projected in the flow direction (m^2), and R_V is the volumetric hydraulic radius (the volume of overlying water per unit plan area of the bed) (m). For practical purposes, R_V can be approximated by the mean flow depth, i.e. the vertical distance between the water surface and the mean bed level. (Note that the flow depths in R_V and A_p cancel, leaving V independent of depth.) Because C_D and A_p are highly variable with flow condition and difficult to estimate, the first square root term is expressed as a single empirical resistance coefficient, F; equation (7.28) is then written as

$$V \quad = \quad \frac{1}{F}\sqrt{R_V}\,\sqrt{2\,g\,S} \tag{7.29}$$

with F determined from river data collected by Bathurst (1978, 1985) as

$$F = 0.05\,Fr^{-0.868}\,Re^{0.12}\,\sigma^{-0.228} \tag{7.30}$$

in which σ is the geometric standard deviation of the bed material size, given by

$$\sigma = \frac{d_{84}}{d_{50}} \tag{7.31}$$

For intermediate-scale roughness ($1 < D/k < {\sim}10$) the flow resistance is considered to be the result of the combined effect of a boundary shear component (as would apply for $D/k > {\sim}10$) and a form drag component (as would apply for $D/k < 1$). The flow velocity is then given by

$$V = \left(\frac{1}{F}\right)^{a}\left(\sqrt{\frac{4}{f}}\right)^{(1-a)}\sqrt{2\,g\,R_V}\,\sqrt{S} \tag{7.32}$$

where F is given by equation (7.30) and f has the value for the bed under small-scale roughness conditions. The exponent a is a function of D/k and varies from 0 (for small-scale roughness) to 1 (for large-scale roughness). Between these limits it has been evaluated from experimental results for hemispherical roughness elements as

$$\begin{aligned} a &= -0.67\ln\left(\frac{D}{k}\right) + 0.992 \\ \textit{and} \quad & 0 \le a \le 1 \end{aligned} \tag{7.33}$$

with k represented by d_{84}. (Note that the data used to derive equation (7.33) suggest the threshold between intermediate- and small-scale roughness to be at about $D/k = 4.5$.)

Equations (7.29) to (7.33) have the advantage of accounting more rationally for resistance effects than those methods using traditional resistance equations, making them more general and less reliant on site specific calibration. They also account for the possible occurrence of transitional turbulent flow at low flows through the inclusion of the Reynolds number in equation (7.30), and provide a continuous transition through the ranges of large- to small-scale roughness. Although they have not been widely tested in natural channels, they performed better than equations (7.22) and (7.23) against independent field data for large- and intermediate-scale roughness conditions (James and Jordanova, 2007).

For river beds with relatively sparse, large, emergent rocks interspersed with completely submerged smaller stones, equations (7.5) to (7.7) have been shown under laboratory conditions to account very reliably for the combination of form and surface resistance. These applications suggested that predictions are fairly insensitive to C_D, and a value of about 1.2 is suggested.

Assessment and recommendations

With the exception of the equations proposed by Jordanova and James (2007), all the other equations presented for describing resistance under conditions of small- intermediate- and large-scale roughness can be expressed as functions of $1/f^{0.5}$ in terms of relative roughness (R/d_{84}), thus enabling their comparison. Such a comparison is presented in Figure 7-5, assuming that $d_{84} = 1.9d_{50}$ where necessary. Although this is not a comparison with data and therefore cannot lead to conclusions about accuracy, it does demonstrate the consistency (or otherwise) between the methods. The equations presented for small-scale roughness (equations (7.16), (7.18) and (7.19)) are seen to be essentially equivalent. The equations for large- and transitional-scale roughness (equations (7.21), (7.22), (7.23), (7.24), and (7.26) with (7.27)) are less consistent in the intermediate-scale roughness range and at considerable variance in the large-scale range. The inconsistency arises from the inappropriateness of the Darcy-Weisbach equation under these conditions and the equations' consequential dependence on empirical data that reflect site-specific conditions. (It should be noted that a ratio of flow depth to roughness height loses all meaning for values less than 1, but d_{84} still has some significance for large-scale roughness conditions if interpreted as the frontal width of the elements.)

Equation (7.21) appears to be representative through the small- to intermediate-scale roughness range (but departs significantly from the others at very low flows). Alternatively, equation (7.17) could be used over the same range with $k_s = 3.5d_{84}$; values of $d = 2.6$ and $e = 0.25$ (i.e. equation (7.18)) would be appropriate for small-scale roughness conditions and $d = 0.48$ and $e = 0.58$ (i.e. from equations (7.26) and 7.27) for intermediate-scale conditions. For large-scale roughness conditions it is recommended that equations (7.29) and (7.30) be used, with site-specific calibration where possible. With F known from equation (7.30) and f from equation (7.21) or (7.17), equations (7.32) and (7.33) could be used to describe the transition through the intermediate-scale range.

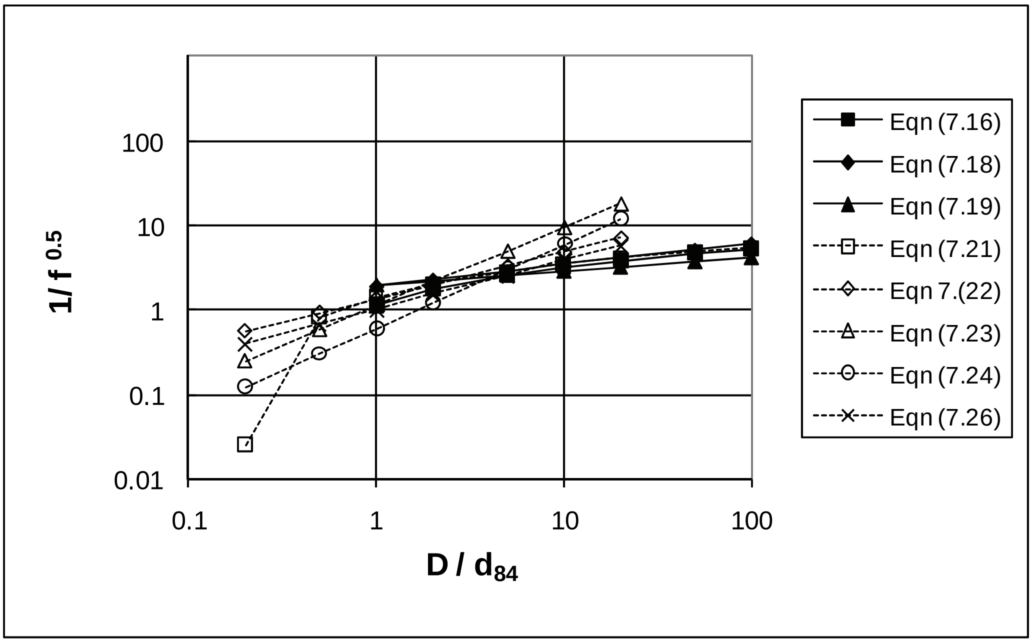

Figure 7-5 Comparison of resistance coefficient formulations for immobile beds

7.4.2 Mobile beds

Under flow conditions sufficient to move the grains, sandy river beds deform into a variety of irregularities known as bed forms. With increasing flow velocity or stream power, the bed forms develop through a recognised sequence through ripples, dunes, a transition to a plane bed, followed by antidunes (Figure 7-6). The lower regime forms (ripples and dunes) add a significant form resistance component to the surface resistance afforded by the grain roughness. Many methods have been proposed for predicting the size and shape of the bed forms, and for determining their resistance effect. Some are purely empirical while others explicitly recognise the form and surface resistance contributions, generally by assigning components of the total resisting force to surface-type shear stress ($\tau^{/}$) and an equivalent shear stress to account for the form resistance ($\tau^{//}$) (Figure 7-6). Only one method is presented here – that proposed by van Rijn (1984), which accounts for the form component through an additional roughness height. Although it is a widely used method, no endorsement over other methods is intended by its inclusion; it has been selected because of its consistency with the methods presented for immobile beds in the previous section through the use of an equivalent roughness height. Other methods in common use are those proposed by Engelund (1966), Brownlie (1983) and White *et al.* (1987). Vanoni (1975) presents a number of the earlier methods. Most of the available methods are awkward to apply and Julien (2002) has suggested Manning's *n* values in the ranges 0.018-0.028 for ripples and 0.020-0.040 for dunes where the value for surface roughness is only 0.014.

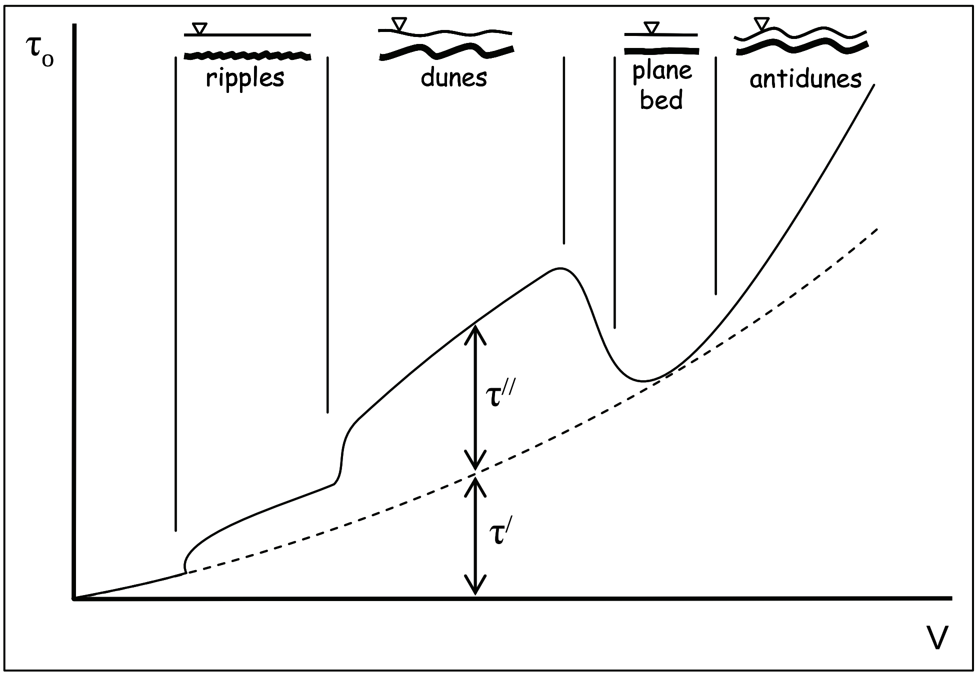

Figure 7-6 **Flow resistance associated with bed forms. The broken line represents the shear resistance associated with grain (surface) roughness and the solid line the total equivalent shear resistance (adapted from Engelund and Hansen, 1967)**

Van Rijn (1984) quantified the total resistance of a deformed bed in terms of the Chézy equation with

$$C = \sqrt{\frac{8g}{f}} = 18\log\left(\frac{12\,D}{k_s}\right) \tag{7.34}$$

(which is almost exactly equivalent to equation (7.16) with $k_s = 3.5d_{84}$ for small scale roughness). Here the bed roughness, k_s, is the sum of components associated with surface and form roughness, i.e.

$$k_s = k_{sg} + k_{sf} \tag{7.35}$$

where

$$k_{sg} = 3d_{90} \tag{7.36}$$

The form roughness height is calculated from the geometric characteristics of the bed forms,

$$k_{sf} = 1.1\Delta\left(1 - e^{-25\Delta/\lambda}\right) \tag{7.37}$$

where Δ is the height of a bed form (m) and λ is its length (m) (Figure 7-7). The bed form length is related to the flow depth by

$$\lambda = 7.3D \tag{7.38}$$

and the height is given by

$$\frac{\Delta}{D} = 0.11\left(\frac{d_{50}}{D}\right)^{0.3}\left(1 - e^{-0.5T}\right)(25 - T) \tag{7.39}$$

in which *T* is a transport stage parameter given by

$$T = \frac{u_*^{/\,2} - u_{*cr}^{\;2}}{u_{*cr}^{\;2}} \tag{7.40}$$

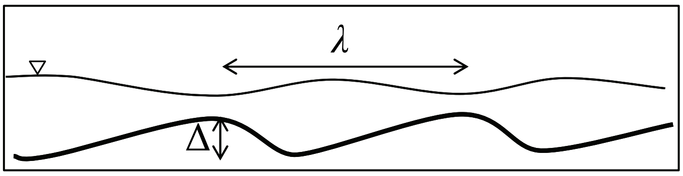

Figure 7-7 Bed form dimensions

In equation (7.40), $u_*^{/}$ is the prevailing shear velocity associated with the surface resistance and u_{*cr} is the shear velocity at the condition of incipient motion of the bed material. The value at incipient motion may be estimated from the Shields diagram (Figure 8-2), bearing in mind that for grain sizes greater than 6 mm, the dimensionless critical shear stress has a constant value, given by

$$\frac{u_{*cr}^{\;2}}{g\,d\,(S_s - 1)} = 0.045 \tag{7.41}$$

in which *d* is the grain size (m) and S_s is the sediment specific gravity (usually assumed to be 2.65).

The method must be applied iteratively because the flow depth (usually the required variable) is needed to determine the bed form characteristics. A flow depth corresponding to a specified discharge (*Q*) can be determined by the following procedure:

1. Calculate the unit width discharge, *q*, (m^3/s/m) as

$$q = \frac{Q}{w} \tag{7.42}$$

where w is the channel width (m).

2. Assume a value of flow depth, D, to be corrected by iteration.

3. Calculate the average flow velocity from

$$V = \frac{q}{D} \tag{7.43}$$

4. Calculate k_{sg} from equation (7.36).

5. Calculate k_{sf} as follows:

   a. Calculate λ from equation (7.38)
   b. Determine u_{*cr} from the Shields diagram (or equation (7.41), if appropriate).
   c. Calculate $C^{/}$, the Chézy resistance coefficient associated with surface roughness from (7.34) using $k_s = k_{sg}$.
   d. Calculate $D^{/}$, the flow depth associated with surface roughness from the Chézy equation, using V from step 3 and $C^{/}$ from step 5.c.
   e. Calculate $u_*^{/}$ from

$$u_*^{/} = \sqrt{g\,D^{/}\,S} \tag{7.44}$$

   f. Calculate T from equation (7.40).
   g. Calculate Δ from equation (7.39).
   h. Calculate k_{sf} from equation (7.37).

6. Calculate k_s from equation (7.35)

7. Calculate the Chézy resistance coefficient for combined surface and form resistance from equation (7.34).

8. Calculate V from the Chézy equation and D from

$$D = \frac{q}{V} \tag{7.45}$$

9. Compare the D calculated in step 8 with that calculated initially assumed in step 2.

10. If the D values in step 2 and 9 are different, repeat steps 3 to 9 with the calculated value until satisfactory agreement is obtained.

7.5 Vegetation resistance

Vegetation is common in and along the banks of rivers, and has a significant influence on the resistance to flow. Vegetation resistance is particularly difficult to account for because of the variability of plant morphology and occurrence, which affects the nature of the resistance phenomenon and the values of resistance coefficients. The nature of resistance is determined by the growth habit of the vegetation, which may be one of four types, *viz.* submerged (the whole plant is below the water surface), free-floating (the plant is unattached to the substratum), floating-leaved (the plants are rooted in the substratum but with most foliage at the water surface), and emergent (rooted plants with leaves and stems protruding above the water surface). These different types require different treatments, and the issue is complicated considerably by the difference in morphology of different species, the change of characteristics with season, the change of characteristics with flow condition (e.g. plants bend under the influence of flow and may present a less resistant surface at high flows than at low flows), and the spatial distribution of the plants. Because of this variability, most results for describing vegetation resistance are empirical and species specific, and numerous investigations have been published (see the bibliography by Dawson and Charlton (1988), for examples). Fully submerged and emergent vegetation has received much attention and rationally based methods have been proposed, which can be used for approximate solutions and may be calibrated for particular situations.

7.5.1 Submerged vegetation

Most methods proposed for estimating the resistance of submerged vegetation have been developed for grasses used for lining artificial channels, but may also be used for grass-type vegetation in rivers and on flood plains. The situation is not dissimilar to that for immobile beds under small- and intermediate-scale roughness conditions, and resistance may also be treated as the surface type. As for immobile beds the resistance coefficient varies with flow condition, increasing significantly as the degree of submergence decreases, similarly to the variation shown in Figure 7.4. A complicating factor in this situation is that the morphology of the stems, and hence the roughness they present, changes with flow condition by bending. Kouwen and his co-workers have developed a method for estimating the resistance coefficient that explicitly accounts for the effect of bending (Kouwen and Unny, 1973; Kouwen and Li, 1980; Kouwen *et al.*, 1981; Kouwen, 1988). The Darcy-Weisbach equation (equation (7.3)) is used, with the resistance coefficient given by a variant of equation (7.12), i.e.

$$\frac{1}{\sqrt{f}} = a + b\log\left(\frac{D}{k}\right) \tag{7.46}$$

in which a and b are coefficients depending on the bent state of the vegetation (Table 7.1), and k is the roughness height (m) given by

$$k = 0.14\,h\left(\frac{\left(\dfrac{MEI}{\tau_o}\right)^{0.25}}{h}\right)^{1.59} \tag{7.47}$$

in which h is the vegetation height (m), M is a non-dimensional representation of stem density, E is the stem material's modulus of elasticity (N/m^2), I is the stem's second moment of area (m^4), and τ_o is the total boundary shear (N/m^2) as given by

$$\tau_o = \rho g D S \tag{7.48}$$

The vegetation lining characteristics represented by M, E, and I are lumped together and treated as one variable MEI (Nm^2). The coefficients a and b depend on whether the stems are erect or prone, which is determined by the relationship of the boundary shear velocity (equation (7.10)) to a critical value given by the lesser of

$$u_{*\,crit} = 0.028 + 6.33\,MEI \tag{7.49}$$

and

$$u_{*\,crit} = 0.23\,MEI^{\,0.106} \tag{7.50}$$

The values of a and b for different conditions defined by the shear velocity are listed in Table 7.1.

Table 7-1 Values of coefficients *a* and *b* for submerged vegetation

Condition	Criterion	*a*	*b*
erect	$u_*/u_{*crit} \leq 1.0$	0.15	1.85
prone	$1.0 < u_*/u_{*crit} \leq 1.5$	0.20	2.70
prone	$1.5 < u_*/u_{*crit} \leq 2.5$	0.28	3.08
prone	$2.5 < u_*/u_{*crit}$	0.29	3.50

Kouwen (1988) proposed two methods for determining MEI for untested surfaces. A value can be determined for a particular grass surface by conducting a ‘board test’, where a large board is held vertical and then allowed to fall over onto the grass. The board will come to rest at an angle, and the height of the higher edge above the ground is a measure of the grass stiffness. The board specifications and the equation relating MEI to the board height are given by Kouwen (1988). Kouwen also correlated values of MEI determined from natural grass linings with the vegetation stem length. He presented three relationships, representing all the data together, data for green grasses, and data for dormant or dead grasses, as follows (all with h in m and MEI in Nm^2).

All data: $$MEI = 223\,h^{3.125} \tag{7.51}$$

Green grasses: $$MEI = 319\,h^{3.3} \tag{7.52}$$

Dead or dormant grasses: $$MEI = 25.4\,h^{2.26} \tag{7.53}$$

7.5.2 Emergent vegetation

Emergent vegetation (e.g. reeds and bulrushes) is common in rivers, flood plains and palustrine wetlands, where it imposes significant resistance on the flow. It may occur extensively or in fragmented distributions, especially as strips along river banks or in patches within river channels (Figure 7-8), each situation requiring different treatment.

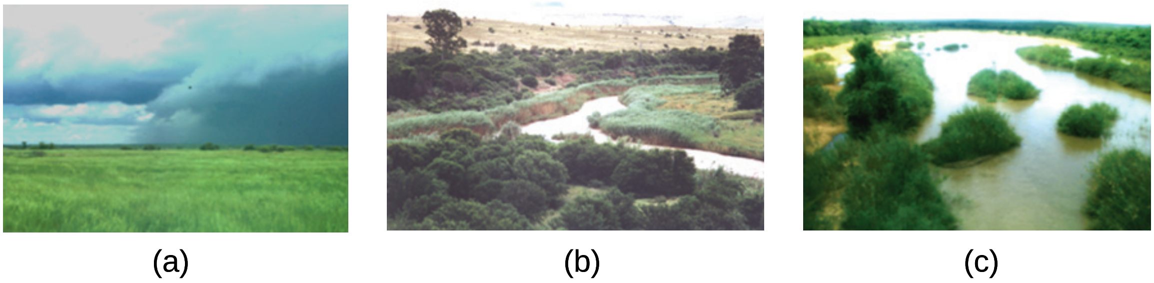
(a) (b) (c)

Figure 7-8 Emergent vegetation : extensive (a), as bank strips (b) and in patches (c)

Extensive emergent vegetation

The resistance of emergent vegetation is predominantly of the form type and use of conventional, surface resistance type equations requires adjustment of the resistance coefficient to compensate for the inappropriate equation form. For example, Figure 7-9 shows the variation with depth of Manning's *n* for foliated stems of *Phragmites australis* in a laboratory flume.

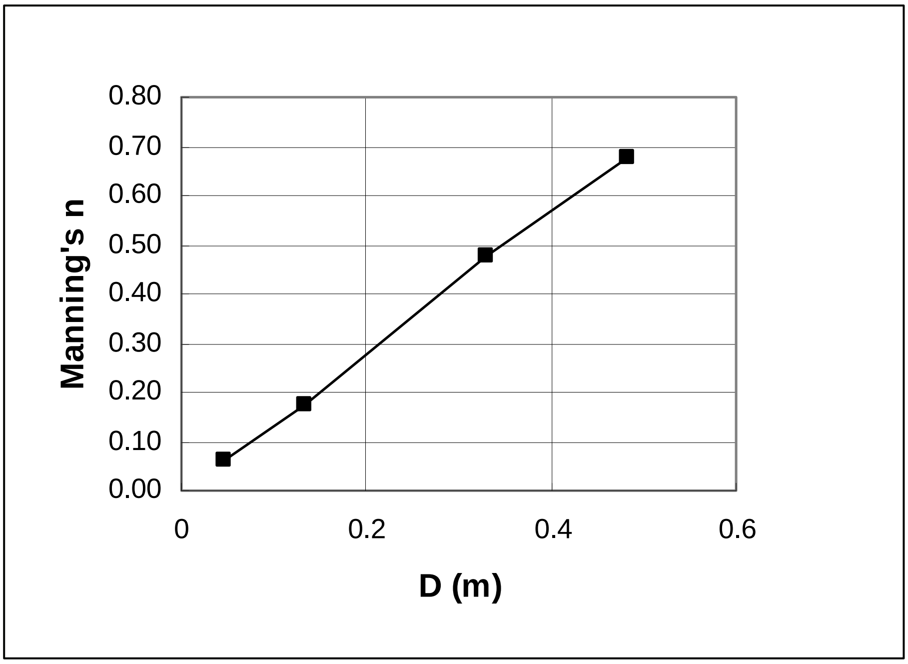

Figure 7-9 Variation of Manning's n with flow depth for flow through emergent vegetation (James *et al.*, 2004)

The equation proposed by James *et al.* (2008) (equation (7.54)) is more appropriate, accounting for the form resistance associated with the drag forces imposed on the flow by the stems, as well as surface resistance imposed by the bed between the stems, i.e.

$$V = \sqrt{\frac{1}{C_S + C_D}}\sqrt{2\,g\,l\,S} \tag{7.54}$$

with

$$l = \frac{s^2}{d} \qquad (7.55)$$

The surface resistance coefficient C_S can be neglected for deep flows with dense vegetation ($ND < \sim 50$, where N is the number of stems per unit area) (James *et al.*, 2004), leading to a particularly simple formula. If required, C_S can be estimated using equation (7.56) with f related to the substrate roughness size in the usual way. The stem spacing (s) and diameter (d) can be estimated from field observation. Values of drag coefficient depend on species, the degree of foliage, and the flow condition as represented by the stem Reynolds number

$$\mathrm{Re} = \frac{V\,d}{\nu} \qquad (7.56)$$

where ν is the kinematic viscosity of water (m^2/s). Estimates of C_D can be made using the compilation of available data presented in Figure 7-10. The data indicated as Reed 1 to 3 and Bulrush were measured for single stems in the laboratory, those indicated as WES are for bulrushes in bulk in an artificial channel (Hall and Freeman, 1994), those indicated as Armanini *et al.* are for willow stems in a laboratory flume (Armanini *et al.*, 2005), and the curve indicated as Standard shows the generally accepted relationship for long circular cylinders (Albertson *et al.*, 1960). The curves representing the upper limit, average and lower limit can be represented mathematically by the equations

$$C_D = 701\mathrm{Re}^{-0.66} \qquad (7.57)$$

$$C_D = 221\mathrm{Re}^{-0.57} \qquad (7.58)$$

and

$$C_D = 51\mathrm{Re}^{-0.43} \qquad (7.59)$$

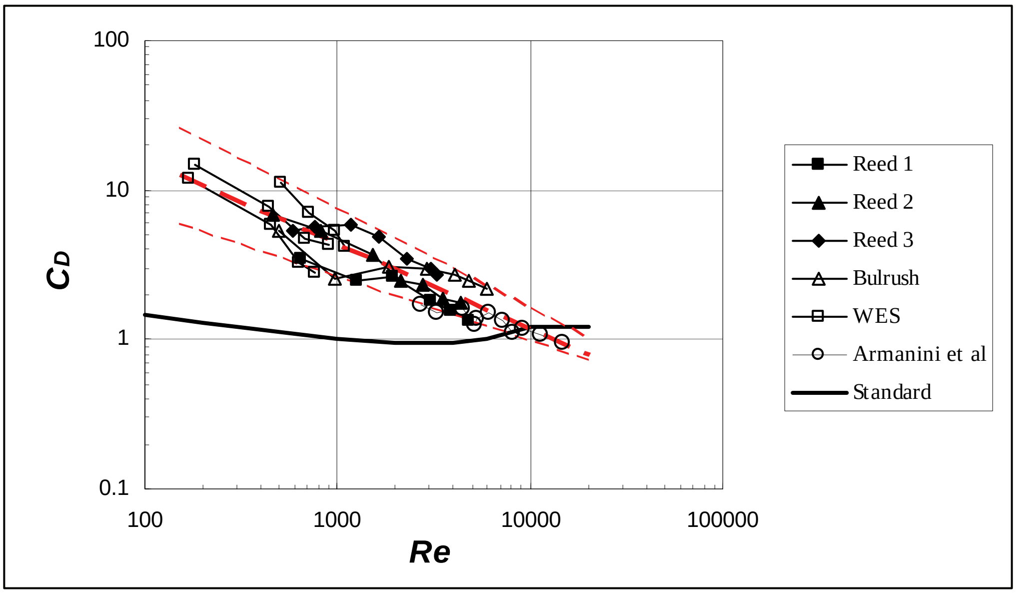

Figure 7-10 Drag coefficient values for emergent vegetation (adapted from James *et al.*, 2008)

Note that an iterative solution is required for the solution of equation (7.5) because the required *V* is needed to calculate *Re*. This can be done by assuming a value for *V* and then iterating the calculations to satisfactory convergence.

If field stage-discharge data are available, it is most convenient and reliable to lump together the terms involving the vegetation and substrate parameters to provide a site-specific resistance equation of the form

$$V = \frac{1}{F}\sqrt{S} \tag{7.60}$$

as suggested by James *et al.* (2004) and Jordanova *et al.* (2006), where *F* is a site-specific resistance coefficient.

Discontinuous Emergent Vegetation

Emergent vegetation frequently occurs in discontinuous patterns in rivers, a particularly common occurrence being as strips along river banks (Figure 7.8b). In such cases, the total channel conveyance can be estimated by subdividing the cross-section into vegetated and clear zones (Figure 7.11), calculating the discharge separately for the different zones and then adding the zonal discharges (James and Makoa, 2006), i.e.

$$Q_{total} \quad = \quad Q_{veg} \quad + \quad Q_{clear} \tag{7.61}$$

where Q_{total} is the total discharge and Q_{veg} and Q_{clear} are the discharges within the vegetated and clear zones respectively.

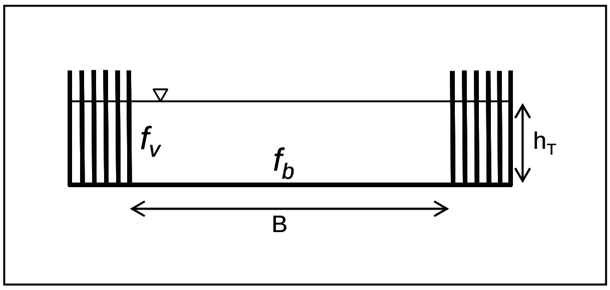

Figure 7-11 Sub-division of cross-section into clear and vegetated zones

The velocity within the vegetation strips can be calculated as described for extensive vegetation in Section 7.5.2. The average velocity within the clear channel section between the vegetation boundaries can be calculated using a conventional resistance equation with a composite resistance coefficient accounting for effects of different surface roughnesses. Hirschowitz (2007) showed that the overall Darcy-Weisbach resistance coefficient can be calculated as

$$f \quad = \quad \frac{f_b\, B + 2\, f_v\, h_T}{B + 2\, h_T} \tag{7.62}$$

in which f_b and f_v are the resistance coefficients for the bed and vegetation interface surfaces respectively, B is the bed width (m), and h_T is the water depth at the vegetation interface (m). (Equation (7.62) is equivalent to the composite roughness equation for Manning's *n* proposed by Pavlovski (1931). It can be easily modified for the situation of vegetation on one bank only.)

The resistance coefficient for the bed (f_b) can be estimated by the methods described in Section 7.4. For the vegetation interface, Kaiser (1984) proposed that

$$f_v \quad = \quad f_{To} + f_I \tag{7.63}$$

in which f_{To} is due to the vegetation structure. Kaiser (1984) suggested $0.06 < f_{To} < 0.10$, but Hirschowitz and James (in prep.) suggest that this term is probably negligible for width-depth ratios greater than about 5. The term f_I is due to the flow interaction, and is given by

$$f_I \quad = \quad 0.18 \log\left(0.0135\,\frac{V_{\inf}^{\;2}}{h_T\,V_v^{\;2}}\right) \tag{7.64}$$

In equation (7.64) V_{inf} is the depth-averaged velocity that would occur as a result of bed resistance only without the influence of vegetation, and can be estimated by the methods presented in Section 7.4. V_v is the unaffected velocity within the vegetation, which can be calculated by the methods in Section 5.2.1. The height h_T is measured in metres (the number 0.0135 is also a length in metres).

These calculations should be carried out in terms of the Darcy-Weisbach resistance coefficients, and only converted to Manning's *n* for the total composite value if it is required in this form. (The bed and vegetation interface *f* values cannot be converted to Manning's *n* values without knowing or assuming the associated values of *R*.)

Emergent vegetation also occurs in patches in rivers, in association with sedimentary bars. The conveyance could be described in the same way as large, discrete roughness elements using equation (7.5), provided appropriate values of C_D are known. In this situation, however, it is common to require local velocity distributions as well as conveyance, and 2-D modeling would then be appropriate and would obviate the need for estimating C_D values.

7.6 Channel macro-form resistance

The reach-scale flow resistance in rivers is influenced by form effects at larger scales than bed forms and rocks at low water levels. Large sedimentary bars and channel bends induce flow patterns and secondary circulations that influence resistance coefficients in models that do not describe the corresponding flow processes.

7.6.1 Bend resistance

The resistance to flow of a channel is significantly increased by the presence of bends (Figure 7.12). The additional resistance is the result of the development of secondary circulation as flow progresses through a bend. This requires energy, which is sourced from the primary flow but dissipated in the secondary circulation decay at the end of the bend.

Figure 7-12 A sequence of bends in a meandering river

The most widely used method for accounting for bend losses in meandering channels is the SCS method, proposed by the United States Soil Conservation Service (1963), which provides an adjustment to the basic value of Manning's *n* in terms of the channel sinuosity (*s*) (which is defined as the distance along the channel between two points divided by the straight line distance between the points). The adjustment, as linearised by James (1994), is expressed as

$$\left.\begin{aligned} \frac{n^{/}}{n} &= \left(\frac{f^{/}}{f}\right)^{1/2} = 0.43\,s + 0.57 && \text{for } s < 1.7 \\ \frac{n^{/}}{n} &= \left(\frac{f^{/}}{f}\right)^{1/2} = 1.30 && \text{for } s \geq 1.7 \end{aligned}\right\} \qquad (7.65)$$

in which $n^{/}$ is the adjusted value. The energy loss is actually associated with the bend characteristics, rather than the sinuosity *per se*, and the SCS adjustment implicitly assumes a particular form of bend to occur commonly in natural channels. James (1995a) applied a secondary circulation model developed by Chang (1983, 1984) to develop a more general, rationally based relationship, i.e.

$$\frac{n^{/}}{n} = \left(\frac{f^{/}}{f}\right)^{1/2} = 0.992\, e^{2.03\, D/r_c} \qquad (7.66)$$

in which r_c is the radius of curvature of the bends (m). (A separate, more complicated equation was developed for $D/r_c > 0.03$, but was subsequently shown to be an unnecessary refinement.)

Liu (1997) proposed a purely empirical equation based on laboratory data, i.e.

$$\frac{n^{/}}{n} \; = \; \left(\frac{f^{/}}{f}\right)^{1/2} \; = \; 0.941\, e^{0.764\, b/r_c} \tag{7.67}$$

in which *b* is the channel width (m).

Very tight inner bends sometimes induce the occurrence of local critical flow with subsequent expansion, causing local acceleration or ‘spill’ resistance (Leopold *et al*., 1960). James and Myers (2002) proposed an empirical equation for bend resistance where this phenomenon is known to occur, i.e.

$$\frac{n^{/}}{n} \; = \; \left(\frac{f^{/}}{f}\right)^{1/2} \; = \; 12.052 \left(\frac{b}{r_c}\right)^{1.152} \left(\frac{D}{r_c}\right)^{0.605} \tag{7.68}$$

Spill resistance is probably uncommon in natural and most designed bend geometries, but its effect is significant and should also be taken cognisance of under low flow conditions in boulder-bed rivers. James and Myers (2002) recommend equation (7.68) if spill resistance is known to occur, equation (7.66) if it is expected not to occur, and equation (7.67) if its occurrence is uncertain.

7.6.2 Bar resistance

The presence of alluvial bars in rivers influences flow patterns and their effects are manifest as apparent resistance in reach scale analyses. Although various types of bars occur (such as braid bars, lateral bars, tributary bars) it is only the bars associated with pool-riffle sequences (Figure 7.13) that have been investigated in terms of reach resistance effects.

Figure 7-13 A pool-riffle sequence in a cobble-bed river

Hey (1988) proposed a form of equation (7.12) for equivalent uniform flow in a reach containing a regular pool-riffle sequence. From previous results he recommended *c* = 2.03 and *a* (including an adjustment for the effect of cross-sectional shape) to be given by

$$a = 11.1\left(\frac{R}{d_m}\right) \tag{7.69}$$

in which d_m is the maximum flow depth across the section (m). Hey assumed that the total roughness height for the reach, D_t, would be the sum of roughness heights representing grain resistance and bar form resistance. This replaces k_s in equation (7.12), and is given by

$$D_t = a\,d\left(\frac{k_{sg}}{a_r\,d_r}\right)^{\left(f_r/f\right)^{0.5}} \tag{7.70}$$

in which k_{sg} is the grain roughness size (m), given by $3.5d_{84}$ as before, d is the reach average flow depth (m), a_r is the value of a for the riffles, given by equation (7.69) with R represented by the flow depth on the riffle, d_r (m). The ratio of riffle to reach average friction factors, f_r/f, is given by

$$\frac{f_r}{f} = \frac{d_r^{\,3}\,W_r^{\,2}\,S_r}{d^3\,W^2\,S} \tag{7.71}$$

in which W and W_r are the reach average and riffle widths (m), and S and S_r are the reach average and riffle slopes.

7.6.3 Compound channels

A compound, or two-stage, channel comprises a main channel with overbank sections or floodplains on one or both sides (Figure 7.14). Compound cross-sections occur in natural rivers, and are frequently engineered to increase channel capacity for flood flows while preserving natural conditions at lower flows in the central portion to meet environmental objectives (James, 1995b). The flow resistance in such a compound channel is enhanced considerably at overbank stages by the interaction between the relatively fast flow within the main channel and the relatively slow flow over the floodplains. The nature of this interaction is complex, and its influence on conveyance can only be assessed realistically through high resolution computational modeling. The interaction between the slow flow on the overbank sections and the relatively fast flow in the main channel can also be accounted for using the Lateral Distribution Method, as described in Chapter 9 and used in the 'Conveyance Estimation System' developed by HR Wallingford (2004). Approximate hand calculation methods for conveyance prediction have been developed from laboratory results for straight compound channels (Ackers, 1993) and for meandering compound channels (James and Wark, 1992); both are presented by Wark *et al.* (1994).

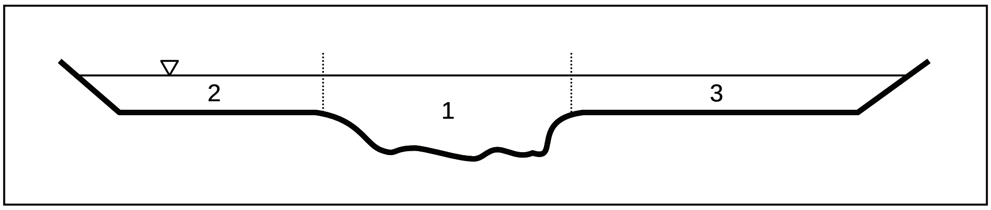

Figure 7-14 Compound channel section

The Ackers (1993) method for straight compound channels involves dividing the cross-section into three zones by vertical planes at the main channel edges, as shown in Figure 7.14. The discharge for a specified stage is calculated as the sum of the three zonal discharges (ignoring the separation planes in the definition of wetted perimeters), which is then adjusted to account for their interaction. The adjustment procedure is complicated, however, and an indication of the range of possible discharge values can be obtained by noting that the unadjusted sum of zonal discharges will invariably *over-estimate* the actual discharge, while the discharge calculated by treating the whole compound section as a unit will invariably *under-estimate* the actual discharge. These two calculations will therefore provide upper and lower possible values; if greater accuracy is required then Ackers's adjustment to the sum of the zonal discharges should be applied.

The James and Wark (1992) method for meandering compound channels is also based on a channel subdivision, but into four zones: (1) the main channel below the flood plain surface, (2) the flood plain within the width of the meander belt, and (3) and (4), the flood plains on either side beyond the extent of meandering. The zonal discharges are again calculated separately, but corrected for interaction effects before being combined. As for the straight compound channel case, the corrections to the zonal discharges are complicated. James and Myers (2002) found that reasonable estimates of conveyance for meandering main channels within meandering floodplains could be obtained with just a horizontal division plane at the bankfull level. The discharge is then the sum of the discharges of the upper and lower channels, with the division plane included in the wetted perimeter for the upper channel but not the lower one to account for interactions. This approach was shown to be adequate for laboratory channels with sinuous main channels and flood plains, but has not been confirmed for the case of straight flood plains, for which the method of James and Wark (1992) was developed.

7.7 Composite resistance

In natural channels there are usually many different features and types of roughness that contribute collectively to resistance. In most hydraulic applications the intention is to determine the value of a single resistance coefficient that accounts for all contributing factors and processes at levels of resolution finer than that at which the predictions are to be made. For 1-D modeling a composite value for a whole river reach is required.

There are two basic approaches to quantifying a reach or cross-section resistance coefficient:

1. Application of experience and information from other sites. The information is provided either in the form of tables with verbal descriptions of site characteristics and typical corresponding coefficient values, or as photographs of sites with accompanying measured values.

2. Synthesis of composite values from the values associated with individual processes, as described in the previous sections.

7.7.1 Tables and photographic guides

Tabulated values of Manning's n for artificial and natural channels are included in many open channel hydraulics text books, such as Chow (1959) and French (1985). Their use has largely been superseded by the more easily interpreted photographic guides, pioneered by Barnes (1967) for North American rivers.

These present photographs of sites with accompanying values of resistance coefficients as determined from measurements of discharge and channel characteristics. The most comprehensive photographic guide is that produced by Hicks and Mason (1998) from information collected in New Zealand rivers. This guide is particularly reliable as the data were all collected for the purpose of its compilation and are therefore mutually consistent. Values of Manning's n and Chézy's C are presented for all sites for a range of discharges, which shows clearly the significant dependence of the values on flow condition.

Although many of the river sites in the Barnes (1967) and Hicks and Mason (1998) guides have counterparts in South Africa there are deficiencies, particularly for the very low flow conditions relevant to environmental flow determinations. Desai (2007) compiled data from 79 South African sites where Instream Flow Requirement studies had been undertaken, and presented these as a computer-based information source. The software is included on CD in the Water Research Commission report by Hirschowitz *et al*. (2007).

7.7.2 Synthesis methods

Various procedures have been proposed for combining local values of resistance coefficients associated with particular surface roughnesses or other channel features to obtain composite cross-section or reach values.

Even local resistance coefficients may have more than one contributing influence. HR Wallingford (2004) proposed combining up to three components, to allow for surface (n_{sur}), vegetation (n_{veg}) and irregularity (n_{irr}) contributions to a local 'unit roughness', n_l. These components may be recognised independently and combined as

$$n_l \quad = \quad \left(n_{sur}^2 + n_{veg}^2 + n_{irr}^2\right)^{1/2} \tag{7.72}$$

The bed of a river can present a surface with spatially varied roughness conditions associated with patchy submerged vegetation, locally sorted sediment grades (such as patches of gravel on an otherwise sandy bed) or variations of bed forms with depth across the section. Flow interactions between regions with different roughnesses can enhance the resistance on a reach scale (Garbrecht and Brown, 1991) and accurate conveyance prediction requires 2-D turbulence modeling. Unless the interactions are extreme (such as with compound channels, as described in Section 6.3) however, quite reliable estimates are possible for longitudinally consistent variations across a section by subdividing the cross-section and summing the constituent conveyances; Garbrecht and Brown (1991) demonstrate that the error incurred by ignoring flow interactions in following this approach is within 5% for channels with width-to-depth ratios exceeding 20, but can be significant in relatively narrow channels. Some 1-D models (e.g. HEC-RAS (US Army Corps of Engineers, 2003)) follow this approach and allow specification of limited variation of n cross sections. An alternative approach is to specify an effective value of Manning's n to represent the resistance of the entire cross-section, n_e. Such composite values may be determined by combining local values under the assumption that there is no flow interaction between sub-sections with different local roughnesses, which is equivalent to the conveyance summation approach. The cross-section with total wetted perimeter P is divided into N sub-sections, each with wetted perimeter P_i (not including the interfaces with adjacent sub-sections) and local resistance coefficient n_i. Various formulations for n_e have been proposed, based on different assumptions relating to the combination of flow characteristics, the most common being the following:

Horton (1933):
$$n_e = \left(\frac{\sum_{i=1}^{N} \left(P_i \, n_i^{3/2} \right)}{P} \right)^{2/3} \tag{7.73}$$

Pavlovski (1931):
$$n_e = \left(\frac{\sum_{i=1}^{N} \left(P_i \, n_i^{2} \right)}{P} \right)^{1/2} \tag{7.74}$$

Bhembe and Pandey (2006) showed that equation (7.73) could also be applied reliably to patchy surfaces over an area by using the volume of water above each distinct roughness area in place of the wetted perimeters.

Equations such as (7.73) and (7.74) neglect the influence of interaction between the sub-sections, which can be considerable in channels with complex cross-section geometries, such as compound or two-stage channels. The conveyance estimation procedure proposed by HR Wallingford (2004) includes a lateral distribution model to account for these effects.

A widely used procedure for synthesising reach values of Manning's *n* was originally proposed by Cowan (1956) and further developed by the United States Soil Conservation Service (SCS) (1963) and Arcement and Schneider (1989). A representative reach value of *n* is obtained by adding a number of adjustment factors to a basic channel factor to account for different effects, as

$$n \quad = \quad \left(n_b + n_1 + n_2 + n_3 + n_4 \right) m \tag{7.75}$$

in which n_b is the basic value for the channel surface, n_1 accounts for the effect of surface irregularities, n_2 for variations in shape and size of the cross-section, n_3 for obstructions, n_4 for vegetation and flow conditions, and *m* for channel meandering. Tables are provided for estimating the basic value, but the methods presented earlier in this chapter can be used. The adjustment factors are also presented in descriptive tables (in the references cited above as well as in textbooks such as French (1985)), although these require a lot of subjective judgement to use. The underlying assumptions of this approach are questionable. The n_1 to n_4 are augmentation values and cannot easily be related to their causes; the tabulated values are based on limited data. There is evidence that the augmentations associated with particular effects depend on the basic n_b value, so they are not independent. The linear superposition of effects implied by equation (7.75) is not really credible; the summation of squares of values in equation (7.72), on the other hand, does have theoretical justification.

The ‘Conveyance Estimation System’ recently produced by HR Wallingford in the United Kingdom for estimating river and floodplain conveyance, is the most advanced synthesis method yet developed (HR Wallingford, 2004). The system includes a ‘Roughness Advisor’ to assist in estimating channel roughness, a ‘Conveyance Generator’ that uses this estimation as well as the channel morphology to predict the channel conveyance, and an ‘Uncertainty Estimator’ for indicating the uncertainty associated with the conveyance calculation. Although the system was developed primarily for flood flows, it should prove useful for some low flow applications as well. The software is freely available from http://www.river-conveyance.net .

Although no entirely satisfactory synthesis method is yet available, careful consideration of the underlying processes and the corresponding formulations presented before, supported by photographic guides, should enable realistic estimates to be made.

7.8 Conclusion

Quantification of flow resistance is a crucial step in the application of hydraulic models for linking the occurrence of water in rivers with their ecological functioning. Selection of an appropriate equation and estimation of a representative resistance coefficient is largely subjective and requires an appreciation of the underlying phenomena and how these are accounted for in the hydraulic model to be used. The resistance coefficient also depends on the physical characteristics of the river channel and the flow condition. While many empirical formulations describing this dependence have been proposed, some lack generality because of their association with inappropriate equations and limited data bases. Site specific data should be used wherever possible to confirm results, calibrate equations or develop reliable coefficient formulations.

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Notation

A: cross-sectional flow area

A_p: projected area of form roughness element

a: coefficient in stage-discharge equation

a: coefficient in logarithmic resistance coefficient equation

a: weighting exponent in large-scale resistance equation

a: constant in logarithmic resistance coefficient equation

a_r: coefficient in logarithmic resistance coefficient equation for riffle

a_x: longitudinal stem spacing

B: channel bed width

b: channel width

b: exponent in stage-discharge equation

b: factor in logarithmic resistance coefficient equation

b: coefficient in logarithmic resistance coefficient equation

C: Chézy resistance coefficient

C_D: drag coefficient

C_s: surface resistance coefficient in surface/form resistance equation

C_x: Jonker resistance coefficient

c: constant in stage-discharge equation

c: coefficient in logarithmic resistance coefficient equation

c: coefficient equation for Manning *n*

D: flow depth

D' flow depth associated with surface roughness

D_t: combined roughness height representing grain and bar form resistance

d: form roughness element frontal width

d: coefficient in power resistance coefficient equation

d: bed particle diameter

d: reach average flow depth

d_m: maximum depth across section

d_p: stem diameter
d_r: flow depth on riffle
d_{50}: substrate material size for which 50% of material is smaller
d_{84}: substrate material size for which 84% of material is smaller
d_{90}: substrate material size for which 90% of material is smaller
E: stem material modulus of elasticity
e: exponent in power resistance coefficient equation
F: large-scale resistance coefficient
F: site-specific vegetation resistance coefficient
Fr: Froude number
f: Darcy-Weisbach resistance coefficient (‘friction factor’)
$f^{\prime}$: Darcy-Weisbach f adjusted for channel sinuosity
f_b: Darcy-Weisbach f for bed
f_I: Darcy-Weisbach f due to flow interaction
f_r: Darcy-Weisbach f for riffle
f_{To}: Darcy-Weisbach f component due to vegetation structure
f_v: Darcy-Weisbach f for vegetation interface
g: gravitational acceleration
h: vegetation height
h_T: water depth at vegetation interface
I: stem second moment of area
k: substrate material size
k_s: Nikuradze roughness size
k_{sf}: bed roughness size for form resistance
k_{sg}: bed roughness size for surface resistance
l: roughness element concentration length
M: stem material density
MEI: composite variable for stem density, elasticity modulus and second moment of area
m: adjustment factor for Manning n to account for channel meandering
N: number of form roughness elements per unit area
N: number of subsections over cross-section
n: Manning resistance coefficient
$n^{\prime}$: Manning n adjusted for channel sinuosity
n_b: basic Manning n for channel surface
n_e: equivalent composite Manning n
n_i: Manning n for subsection i
n_l: HR Wallingford ‘unit roughness’
n_{irr}: Manning n for irregularity
n_{sur}: Manning n for surface
n_{veg}: Manning n for vegetation
n_1: adjustment to Manning n to account for surface irregularities
n_2: adjustment to Manning n to account for cross-section shape and size variations
n_3: adjustment to Manning n to account for obstructions
n_4: adjustment to Manning n to account for vegetation and flow conditions
P: proportion of surface covered by form roughness elements
P: wetted perimeter

P_i: wetted perimeter of subsection i
Q: discharge
Q_{clear}: discharge in clear (unvegetated) zone of cross-section
Q_{total}: total discharge over cross-section
Q_{veg}: discharge in vegetated zone of cross-section
q: discharge per unit width
R: hydraulic radius
Re: Reynolds number
Re^*: shear Reynolds number
R_V: volumetric hydraulic radius
r_c: radius of curvature of channel bend
S: channel slope
S_r: slope of riffle
S_s: sediment specific gravity
s: average clear spacing between form roughness elements
s: channel sinuosity
T: transport stage parameter
u_*: shear velocity
u_*': shear velocity associated with surface resistance
u_{*c}: shear velocity at incipient motion
V: cross-section average velocity
V_{inf}: depth-averaged velocity resisted by bed shear only
V_v: unaffected velocity within vegetation
W: reach average channel width
W_r: riffle width
w: channel width
y: maximum flow depth in cross-section
Δ: alluvial bed form height
λ: alluvial bed form length
ν: kinematic viscosity of water
ρ: density of water
σ: standard deviation of bed material size
τ_o: boundary shear stress

8. CHANNEL MAINTENANCE FLOWS

V Jonker and MJ Shand

8.1 Introduction

Rivers are open, dynamic systems that experience continuous movement of energy and matter, with changes occurring over a range of time scales. The physical characteristics of the river channel are determined by geomorphological and hydrological processes responsible for eroding the channel bed and banks and supplying, transporting and depositing the sediments which comprise many channel features (Dollar and Rowntree, 2003). Changes to channel morphology (channel form and substrate) affect aquatic habitat, as the response of the instantaneous discharge to channel form and substrate determines ecosystem functioning through the availability of physical (hydraulic) habitat for aquatic species.

For many aquatic organisms, the channel bed offers refuge from floods, droughts and extreme temperatures, with some species using the channel bed to deposit or incubate eggs. Furthermore, the organic matter trapped in the interstitial spaces between bed particles provides nutrients, while the variation in macro channel geometry and form offers habitat diversity. An understanding of the inter-relationship between channel form and flow and sediment dynamics is therefore imperative when assessing the impacts of a modified flow regime on a river ecosystem across various spatial and temporal scales or when attempting to mitigate the possible environmental impacts of changes in flow and sediment regimes.

The aim of this chapter is to present hydraulic-based models and techniques that are applied within an ecohydraulics context and which are aimed at quantifying those components of the flow regime that are important for maintenance of channel form and substrate. The maintenance of channel form considers processes that take place in the medium to long term (10 to 100 year period), while the maintenance of substrate involves the seasonal flushing of fine materials from the interstitial bed spaces as well as the ‘disturbance’ and transport of individual bed particles.

The second part of the chapter is dedicated to a brief description of key concepts related to fluvial geomorphology, while the third part describes specific hydraulic-based models and theories that are relevant for the quantification of channel maintenance flows. It is important to note that this chapter should be read in conjunction with Chapter 2, which provides a framework for the geomorphological classification of rivers and introduces essential concepts in fluvial geomorphology such as longitudinal zonation, morphological units and hydraulic biotopes.

Box 8.1

The Berg River Dam

The 65 m high Berg River Dam in the Western Cape Province was completed in 2008 and forms part of the Berg Water Project which will augment the supply of water to the City of Cape Town. The outlet works of the dam were the first in South Africa designed to release both the low and the high flow components of the Reserve and have the capacity to release a maximum 'channel maintenance flow' of 160 m^3/s.

Environmental flows being released from the Berg River Dam

8.2 Key concepts

8.2.1 Channel type

River channels can be classified into three main types, namely bedrock, alluvial and mixed channels. In bedrock channels, the channel form is mainly determined by the geology of the river bed and its resistance to erosion, while in contrast, alluvial channels form within alluvium (sediment) that is transported by the river. Unlike bedrock channels, where there is no direct correlation between channel form (morphology) and the flow and sediment regime, the form of an alluvial channel is a direct result of the balance between the available sediment and the sediment transport capacity of the river. Consequently, alluvial channels are constantly adjusting whenever flow and/or sediment related changes are imposed. Channels which display a mixture of bedrock and of alluvial sediments are known as mixed channels.

8.2.2 Channel form

Channel form concerns the physical form of a river channel as defined by channel geometry and bed form geometry. Channel geometry describes the cross-sectional shape (bankfull width and depth) of a river channel, which generally increases in the downstream direction. Channel form geometry refers to the spacing, gradient and physical dimensions of macro-scale bed forms comprising the channel morphology, e.g. pool and riffle morphological units.

8.2.3 Channel pattern

Channel pattern classification refers to the planimetric form of the river. In upland areas, which are often characterised by bedrock channels that form the headwater tributaries of rivers, the channel pattern usually closely follows that of the incised valley between hillslopes. Along lower reaches, however, which are most frequently dominated by alluvial or mixed channels, the channel pattern adjusts to the flow and sediment regimes and the morphology of the land. Generally, channel patterns can be classified into two broad categories namely single-thread and multi-thread channels. Single-thread channels may be further classified into straight or meandering channels. Straight or meandering channels are distinguished by the degree of sinuosity, which is defined as the length of the active (thalweg) channel divided by the valley distance (Richards, 1982). Straight channels are generally classified as channels with a sinuosity less than 1.5, while meandering channels have a sinuosity of 1.5 or more. Multi-thread channels are classified as either braided or anastomosing. In the case of braided channels, two or more channels are divided by alluvial bars, while anastomosing channels are characterised by multi-thread channels separated by stable islands.

8.2.4 Substrate

Substrate is a general term that encompasses all of the material that constitutes the channel boundary. In alluvial rivers, substrate characteristics are most commonly described in terms of substrate particle sizes. Table 8.1 provides a classification of the different particle sizes as defined by the Wentworth scale, which is based on the length dimension of the median axis. The phi (ϕ) scale is also often used to define particle size and is equal to the negative logarithm (base 2) of the particle size in millimetres.

Table 8-1 Grade scales for substrate particle size (adapted from Brakensiek *et al.*, 1979)

Class (Wentworth)	**Diameter (mm)**	**Phi**
Boulder	> 256	-12 to -8
Cobble	64 to 256	-8 to –6
Gravel	2 to 64	-6 to –1
Sand	0.0625 to 2	-1 to 4
Silt	0.0039 to 0.0625	4 to 8
Clay	< 0.0039	8 to 12

Other characteristics of substrate, which are of importance within an ecohydraulics context, include sorting (the variation in particle size as described by the particle size distribution), particle shape (typically described in terms of roundness and sphericity), and the arrangement and associated bulk properties of the substrate (described in terms of orientation, stability, porosity, density and degree of embeddedness). All of these characteristics have a direct impact on the biotic productivity of the substrate.

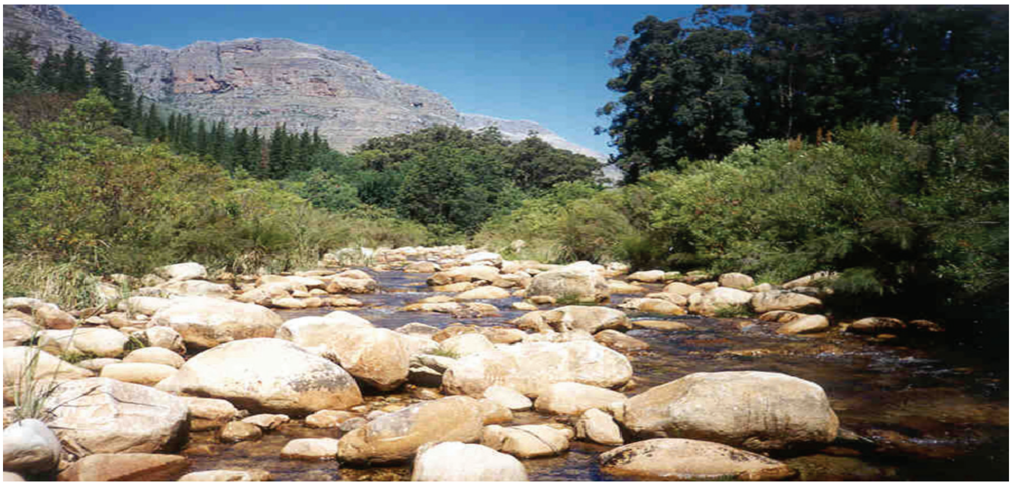


Figure 8-1 Typical cobble and boulder bed river

8.2.5 Sediment transport

The mathematical description of sediment motion in rivers is mainly concerned with two phases, namely the initiation of particle movement and the actual transport of sediment. The total sediment load in a river includes bed load, suspended bed-material load and wash load. Bed load represents bed particles that are transported along the river bed by means of rolling or saltation, while suspended bed-material load represents bed material that is carried in suspension by the fast flowing river and will be deposited once the flow velocity and turbulence decrease. The actual vertical distribution of sediment depends on the sediment and flow characteristics. Wash load primarily represents clays and silts which are carried in suspension and which may never settle out.

Sediment discharge refers to the sediment load rate transported through a cross-section in volume or mass per unit time, e.g. tons per year. Sediment concentration refers to the weight or volume percentage of sediment being transported in a river. Numerous sediment transport equations have been developed over the last century. Most of these equations have been ‘calibrated’ based on laboratory and, in limited cases, field data and may be used to estimate either the sediment discharge or the sediment concentration in ppm or % weight. Generally, sediment transport equations may be classified into two groups, *viz*. those that quantify bed load and suspended load separately and those that predict the total sediment load, with no distinction between the bed load and suspended load fractions. In most cases, the equations do not accommodate wash load. Equations describing the transport of bed load are generally either empirical or derived by means of sophisticated statistical analyses. The different bed-load equations are often similar and can be categorised into three groups displaying similar type equations (Graf, 1971), *viz*. Du Boys, Schoklitsch and Einstein type equations. Examples of equations describing the total load include the Engelund and Hansen (1967), Ackers and White (1973), Yang (1973), Rooseboom (1974) and Basson

(1999) equations. When applying the above equations, it is important to be aware of the fact that the results differ appreciably and provide a range of possible values, which should be interpreted as such.

The amount of sediment that is transported by rivers depends on two factors, *viz*. the availability of sediment eroded from the river banks or upstream catchment and the ability of the river to actually transport this sediment. Rivers are therefore either supply limited or capacity limited. In the case of a river's sediment transport capacity being less than that required to transport the influx of sediment from upstream, sediment is deposited, which leads to aggradation. On the other hand, when the transport capacity of a river exceeds the actual sediment concentration, erosion will take place, which results in scouring of the banks or a lowering of the river bed (degradation). For South African rivers carrying fine sediments, Rooseboom (1992) states that sediment concentrations and loads are generally determined by the availability of sediment rather than the carrying capacity of the river.

8.2.6 Flow and sediment regimes

Within the context of flow and sediment movement in rivers, the term ‘regime’ refers to something that happens on a regular or consistent basis, with a characteristic pattern over time. A river's ‘flow regime’ therefore refers to the unique flow pattern that characterises the river system as described by magnitude, frequency, variability and temporal distribution, which in turn drives various morphological processes and determines channel form. Similarly, ‘sediment regime’ refers to the characteristic transport of sediment down a river channel as described by sediment load, sediment size and the spatial and temporal distribution of sediment transport. A river's sediment regime is closely linked to the geology and erodibility of the catchment as well as the ability of the flow in the river to transport sediment.

8.2.7 Morphologically significant discharges

Although it has been proposed that a single discharge, the ‘dominant discharge’, can be associated with channel formation and has an equivalent effect to that of the range of flows which influences channel form (Inglis, 1941), the currently accepted notion is that channel morphology is made up of a number of components, each of which has its own response to variable flows and therefore its own ‘dominant’ discharge (Prins and De Vries, 1971),

A key issue related to the specification of channel maintenance flows therefore concerns the quantification of discharges which ‘dominate’ different channel formation processes. These discharges may be defined either in terms of their hydraulic significance or their sedimentological significance. Examples of hydraulically significant discharges include flows which exceed the critical shear stress of the bed sediments or flows that fill the river channel to its banks (the bankfull discharge) and above which the river spills into the floodplain; sedimentologically significant discharges include the so-called effective discharge, i.e. the discharge that transports the most sediment over time.

Because of the difficulties associated with quantifying the bankfull or effective discharge (due to insufficient or inaccurate data), various attempts have been made to express the hydrological significance of dominant discharges in terms of their frequencies of occurrence or other hydrologically significant indices. In perennial rivers, various researchers have found that bankfull discharge displays a consistency in terms of frequency of occurrence, with recurrence intervals of between 1 and 4 years. However, it has been argued that, especially in drier climates, the bankfull discharge does not represent the dominant discharge related to channel form, as the river rarely achieves bankfull level for significant periods of time. For these ephemeral rivers, characterised by infrequent high flood peaks, it has been suggested that channel form is related to higher, less frequent events (such as the 1 in 10 year flood), which do not necessarily correspond to the bankfull discharge. This implies that hydrology and climate are important considerations for determining the effectiveness of floods to maintain channel form.

In addition to the discharge that dominates channel formation, a range of other discharges are also significant in terms of channel maintenance for ensuring a healthy and productive aquatic environment. These include sediment flushing flows and bed disturbance flows.

8.2.8 Equilibrium adjustments

In alluvial rivers, channel processes include sediment transport as well as the erosion and deposition of sediment. These processes relate to changes in the flow and sediment regime and work towards establishing a condition of dynamic equilibrium. As such, the concept of a ‘regime’ channel, as defined by Richards (1987), applies, i.e. a self-formed channel which, when subjected to relatively uniform governing conditions, is expected to show a consistency of form or average geometry adjusted to transmit the imposed water and sediment regime. Under pristine conditions, dynamic equilibrium enables river systems to maintain sustainable river environments through extreme hydrological events such as floods or droughts. Although the channel form reacts to the unique flow and sediment regimes introduced by these extreme events, over time the channel processes and the tendency of the system to adjust towards equilibrium enable the system to recover when the flow and sediment regimes return to normal. However, when changes in land-use or large-scale water resource developments are introduced, which permanently alter the flow and sediment regimes, the river system permanently adjusts to the associated changes in these regimes, with significant impacts on river morphology and riverine ecosystems.

8.3 Channel maintenance flow applications

Whereas the previous section of this chapter dealt with key concepts related to fluvial geomorphology as well as the processes which drive morphological change in river systems, this section presents hydraulics-based models and techniques that are applied within an ecohydraulics context and are aimed at quantifying those components of the flow regime that are important for maintenance of channel form and substrate.

8.3.1 Bed disturbance flows

Within an ecological context, ‘bed disturbance’ refers to the initiation of movement of individual bed particles. The intensity of bed disturbance is thus often measured in terms of the proportion of bed particles that has moved (Cullis *et al.*, 2008), irrespective of whether the particles have been transported over some distance or simply rolled over.

Baker and Costa (1987) attempted to determine the relationship between extreme floods and sediment movement and found that, in alluvial rivers, the highest shear stress and stream power per unit area are not necessarily associated with the largest floods, due to the fact that an increase in discharge is often accommodated by width adjustments. Jonker *et al.* (2002) found that within cobble and boulder bed rivers, floods with recurrence intervals of between 1 and 4 years could initiate movement of bed particles up to the 95th percentile value along riffles, while the same floods were only capable of moving bed particles up to the 35th percentile value within pools. In bedrock–controlled rivers, where an increase in discharge is often translated into a corresponding increase in depth and velocity, characterised by high values of shear stress and stream power, Wohl (1992) demonstrated that boulder bars only become mobilised during floods with recurrence intervals in the order of 200 years.

Ecological Significance

In gravel and cobble-bed rivers, many aquatic organisms are dependent on the channel bed for their survival. Depending on the species and life-cycle, the channel bed provides refuge from floods, shelter during droughts and from extreme temperatures, as well as interstitial spaces in which to lay eggs. The bed of cobble- and boulder-bed rivers is often referred to as a ‘faunal reservoir’, as it provides a source of individuals for recolonisation of a stream if invertebrate populations are depleted by adverse conditions (Cullis *et al.*, 2008). To ensure a healthy and biodiverse ecosystem in these rivers, it is imperative that the channel bed is maintained in a condition that will allow for the habitat requirements and functions of aquatic organisms to be met. Within an ecohydraulics context, the initiation of movement of bed particles is a critical component of this maintenance process, as it corresponds to the initiation of bed disturbance and the associated ecological implications including the replenishment of nutrients and oxygen, the removal of metabolic wastes and a ‘balancing’ of the aquatic system in terms of species composition. In order to maintain a healthy and productive aquatic environment downstream of dams, it is therefore imperative that the environmental flow release incorporates a substrate disturbance component, the primary aim of which is to mimic the timing, frequency and extent of bed disturbance under natural conditions.

Incipient Motion Theory

The common rationale behind models which predict sediment movement (and entrainment) in rivers, is based on some ‘critical’ state above which bed particles begin to move. This ‘threshold’ condition can be defined in different ways and a variety of models and equations have been developed to define the critical condition for sediment movement in terms of various hydraulic and physical parameters. In general, incipient motion theory aims to quantify the critical condition for sediment movement in terms of flow velocity, shear forces or stream power. Furthermore, incipient motion theories often distinguish between uniform and non-uniform bed particles.

Uniform Substrate Sizes: Critical velocity

A quantification of critical velocity, based on field data, for a range of particle sizes above which particle movement is initiated (erosion), maintained (transport) or terminated (deposition) was undertaken by Hjulström (1939). A shortcoming of this approach, however, is that these are purely empirical relationships which were developed from site specific data and consequently they should be applied with caution.

Uniform Substrate Sizes: Critical shear stress

Another approach towards the definition of critical conditions for sediment movement, which is also the most widely used method, relates to the concept that a critical shear stress is required to set a particle in motion. Based on the relationship between shear and frictional forces, the classic equation which defines the equilibrium of moments of drag and lift forces acting on a bed particle and its submerged weight about a pivot axis, taking into consideration the inclination of the river bed from the horizontal as well as the angle of repose of the particle (Graf, 1971), may be reworked to define the critical shear stress as

$$\tau_c = \theta_c g d \left(\rho_s - \rho\right) \tag{8.1}$$

in which τ_c is the critical shear stress (N/m^2), θ_c is the dimensionless critical shear stress parameter, g is gravitational acceleration (m/s^2), d is the particle diameter (m), ρ_s is the particle density(kg/m^3), and ρ is water density (kg/m^3).

Based on experimental data, Shields (1936) related θ_c to another dimensionless parameter, termed the 'roughness Reynolds number' (R_e*), defined as

$$R_e^* = \frac{V^* d}{v} \tag{8.2}$$

where V^* is the shear velocity ($\approx \sqrt{gDs}$) (m/s), D is the flow depth (m), s is the energy slope (m/m), and v is the kinematic viscosity of water (m^2/s).

The average boundary shear stress (τ_b) is given by

$$\tau_b = \rho g s D \tag{8.3}$$

For a particle to move, the actual shear stress (as defined by equation (8.3)), must therefore exceed the critical value.

Figure 8.2 depicts critical flow conditions in terms of the relationship between θ_c and Re^* and shows that, for larger values of Re^*, θ_c approaches a constant value of 0.045 (Yalin & Karahan, 1979).

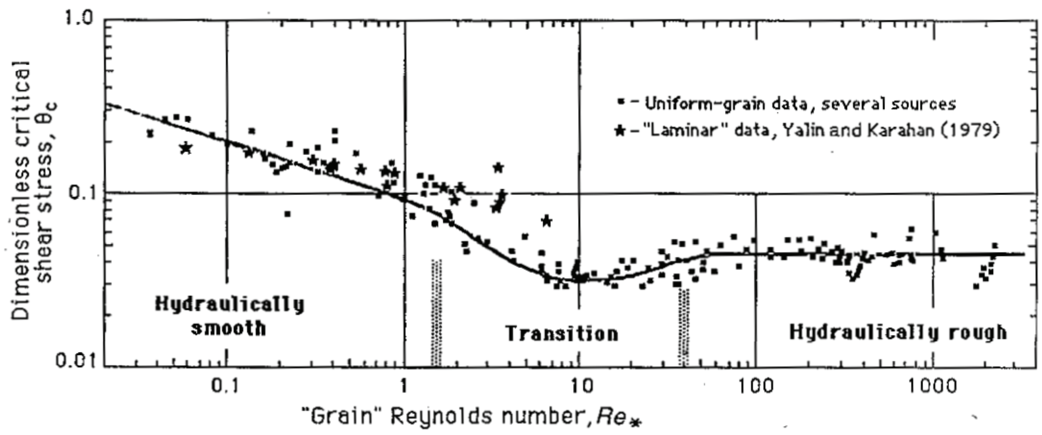


Figure 8-2 Shields diagram (Yalin and Karahan, 1979)

Uniform Substrate Sizes: Stream power

Another approach towards defining the threshold condition for cohesionless sediment movement on uniform beds was developed by Rooseboom (1974) and is based on the principle of minimum applied unit stream power and the hypothesis that where alternative modes of flow exist, that mode of flow which expends the least amount of unit power will be followed. Therefore, fluid flowing over movable material will only transport the material if it will result in a decrease in the amount of unit power being applied.

Based on experimental data from Yang (1973), Rooseboom (1992) calibrated equations defining the critical condition for sediment movement under both laminar and turbulent boundary conditions. This resulted in equation (8.4) for values of $\frac{\sqrt{gDs}\,d}{\nu} < 13$, i.e. with smooth turbulent or completely laminar flow over a smooth bed, i.e.

$$\frac{\sqrt{gDs}}{V_{ss}} = \frac{1.6}{\frac{\sqrt{gDs}}{\nu}.d} \tag{8.4}$$

and equation (8.5) for rough turbulent flow, i.e. for values of $\frac{\sqrt{gDs}\,d}{\nu} > 13$, i.e.

$$\frac{\sqrt{gDs}}{V_{ss}} = 0.12 \tag{8.5}$$

in which with V_{ss} is the settling velocity (m/s).

Equations (8.4) and (8.5) are depicted graphically in Figure 8.3.

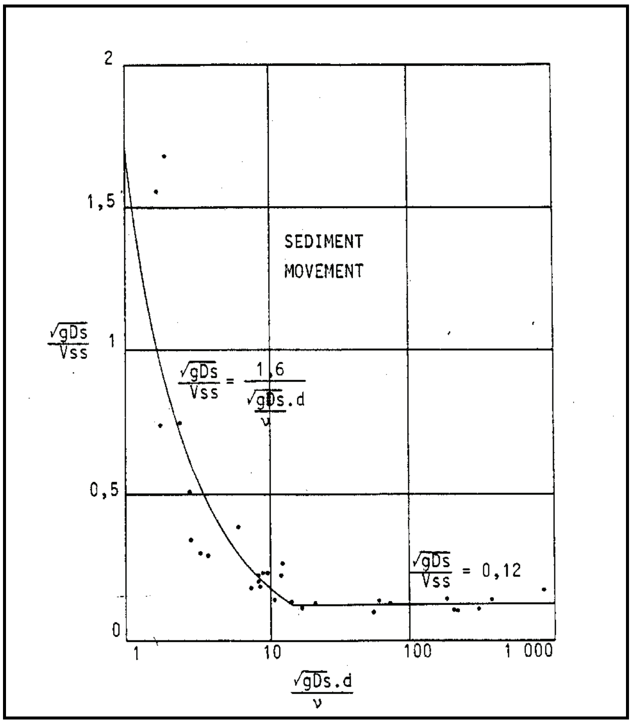


Figure 8-3 Critical conditions for cohesionless sediment particles (Rooseboom, 1992)

Non-Uniform Substrate Sizes: Critical shear stress

Most incipient motion theories have been developed and calibrated based on data for uniform bed particle sizes and are therefore only applicable to rivers with a fairly uniform substrate size distribution. In gravel, cobble and boulder bed rivers, the heterogeneous nature of the substrate particles and the effects of shielding and armouring, complicate the quantification of critical conditions for sediment movement in that the conventional sediment entrainment equations are no longer valid without some form of adjustment. Wiberg and Smith (1987) for example, found that due to the relative protrusion of particles into the flow as well as differences in the particle angle of repose, particles at the surface of a poorly sorted bed can have critical shear stresses that differ significantly from the critical shear stresses associated with the same particles when placed on a well-sorted bed of the same size. In general, on a non-uniform bed, larger particles of a size distribution are moved at shear stresses that are lower than those required on a uniform bed, while the finer sized fractions require greater shear stresses.

Extensive research has been conducted in order to estimate the critical shear stress in mixed bed sediments. Some researchers found that, in mixed bed rivers, particles move over a much narrower range of discharges than previously anticipated. This led to the so-called ‘equal mobility theory’ (Parker *et al.*, 1982; Andrews, 1983), which states that in a mixed-size bed, all particle sizes move at essentially the same shear stress, which can be calculated based on a single representative diameter – mostly assumed to be the median size of the bed particles (d_{50}). Equation (8.1) can therefore still be used to calculate the critical shear stress in mixed bed sediments, however, to accommodate the effects of exposure and bed heterogeneity on incipient motion, lower values of θ_c, ranging between 0.01 and 0.20 have been recommended (Church, 1978; Andrews, 1983; Carson and Griffiths, 1989).

Another approach aimed at predicting the dimensionless critical shear stress (θ_c) associated with the initiation of movement of individual size particles in a heterogeneous bed, is based on the finding that the value of θ_c varies as a function of the ratio of the specific bed particle size percentile being considered (d_i) to the median bed particle size (d_{50}). This provides a measurement of the hydraulic protection of individual bed elements due to their relative size on the bed and leads to the following type of equation:

$$\theta_c = a\ (d_i / d_{50})^b \qquad (8.6)$$

Table 8.2 lists the range of *a* and *b* coefficients in equation (8.6), as derived from a number of studies for bed particles that are mainly in the gravel size range. The variation in the values of these coefficients may be attributed to the specific hydraulic and substrate conditions at the various study sites, which emphasises the site specific nature of these types of equations, which makes it difficult to extrapolate the results.

Table 8-2 Exponents for defining critical shear stress in mixed bed sediments (adapted from Petit, 1994)

a	*b*	d_i/d_{50} Range	Reference
0.088	-0.98	0.045-4.2	Parker *et al.* (1982)
0.083	-0.87	0.3-4.2	Andrews (1983)
0.045	-0.68	0.4-5.9	Milhous (1973)
0.045	-0.68	0.5-10.0	Carling (1983)
0.045	-0.71	0.67-5.3	Hammond *et al.* (1984)
0.089	-0.74	0.1-2.0	Ashworth and Ferguson (1989)
0.047	-0.88	0.04-1.2	Ferguson *et al.* (1989)
0.049	-0.69	0.15-3.12	Ashworth *et al.* (1992)

Wiberg and Smith (1987) assumed that the velocity profile of the water could be extrapolated down to the level of the grains on the bed, allowing the forces on individual grains to be calculated and the critical shear stress for each grain to be predicted. By allowing for two length scales (the particle diameter and the bed roughness), they developed a methodology to calculate the critical shear stress of individual bed particle sizes as a function of the non-dimensionalised particle diameter.

Non-Uniform Substrate Sizes:Critical discharge

Bathurst (1987) adopted the Schoklitsch (1962) approach and, based on empirical relationships, developed equations (8.7) and (8.8) to calculate the critical discharge per unit width for movement of a specific particle size percentile (d_i) on a bed with a range of particle sizes. Although the equations were calibrated with field data, they are purely empirical, which complicates their general applicability.

$$q_{cr} = 0.15\, g^{0.5}\, d_r^{1.5}\, s^{-1.12} \tag{8.7}$$

$$q_{ci} = q_{cr}\, (d_i / d_r)^b \tag{8.8}$$

In theses equations q_{cr} is the critical water discharge per unit width for a uniform particle size bed ($m^3/s/m$), s is the channel gradient, d_r is the reference particle size (= d_{50}) (m), q_{ci} is the critical water discharge per unit width for movement of particle d_i ($m^3/s/m$), and b is $1.5\,(d_{84}/d_{16})^{-1}$

Non-Uniform Substrate Sizes: Stream power

Cullis *et al.* (2008) adapted Rooseboom's (1992) unit stream power approach to define the condition of incipient motion for a bed particle of diameter d_i in a heterogeneous cobble and boulder bed. By introducing into equation (8.5) a non-dimensional parameter, defined as the ratio of bed particle diameter (d_i) to absolute roughness (assumed equivalent to d_{84}), a probability analysis of the likelihood of movement of individual bed particles was undertaken. Based on field data collected in two cobble and boulder bed rivers in the Western Cape province, the following equation was subsequently calibrated to define the condition of incipient motion in cobble and boulder bed rivers with non-uniform particle size distributions:

$$\frac{\sqrt{gDs}}{V_{ss}}\left(d_i/d_{84}\right)^{1/3} = 0.12 \tag{8.9}$$

Relative Bed Stability

An index which is often used to describe the 'stability' of an alluvial river bed in terms of movement of the bed particles is the so-called 'Relative Bed Stability' (RBS), which is defined as the ratio of critical shear stress (τ_c) for initiating movement of a bed particle to the actual (or estimated) boundary shear stress (τ_b), i.e.

$$RBS = {}^{\tau_c}\!/_{\tau_b} \tag{8.10}$$

An RBS value larger than 1 would therefore indicate that the bed is stable.

8.3.2 Flows for maintaining channel form

The maintenance of channel form is affected by a wide range of discharges and processes that take place in the medium to long term (10 to 100 year period). Furthermore, particularly in semi-arid climatic regions such as South Africa, because of the temporal variability of flow and sediment regimes, a natural river is continually under adjustment. Yet, it has been observed that rivers tend towards a state of quasi or dynamic equilibrium by adjusting their cross-sectional geometries, channel slopes and channel patterns. Consequently, various models and equations have been developed in an attempt to quantify the relationship between channel form and characteristic discharges.

In order to predict the impact of a modified flow and sediment regime on downstream channel morphology and the associated ecological habitat, it is necessary to be able to predict the changes in channel form that will occur. These relate to changes in channel width and depth as well as changes in channel gradient, channel pattern and the formation and spacing of macro-scale bed forms, e.g. pool-riffle structures, in rivers with larger sized bed particles. Whereas these changes may be significant in alluvial rivers, in bedrock-controlled channels the morphology of the channel is related more to the resistance of the channel boundary material to erosion than to discharge, except in the case of extreme flood events.

Ecological significance

Changes to channel form not only affect the physical dimensions and pattern of the river channel, with an associated impact on riparian vegetation and channel conveyance, but also the aquatic habitat, as the response of the instantaneous discharge to channel form determines ecosystem functioning through the availability and variability of physical (hydraulic) habitat for aquatic species. The construction of a dam drastically alters the flow and sediment regime of the river downstream, which could lead to significant changes in channel form. This may result in a serious impact on the riverine ecosystem and has to be mitigated by incorporating the release of channel maintenance flows into the dam operating rules.

Characteristic Discharge

Jonker *et al*. (2002) have shown that the geometry and localised particle size distributions characteristic of macro-scale bed forms (e.g. pool-riffle structures) in cobble-bed rivers in the Western Cape, display a good correlation with bed shear stresses during bankfull discharge, which has been linked to recurrence intervals of between 1 and 3 years. Dollar and Rowntree (2003) found that there appears to be no consistency in terms of the frequency of occurrence of bankfull flows in three South African river systems and concluded that two sets of discharges are of morphological significance in terms of channel maintenance: (1) effective discharges in the 5% to 0.1% or 5% to 0.01% flow duration classes, which are responsible for the bulk of the bed-material transport and largely determine the morphological adjustment of the active channel (Box 8.2); and (2) a 'reset' discharge, equivalent to the 1 in 20 year flood, which maintains the macro-channel and mobilises the entire bed. Beck and Basson (2003) suggested that, although it is difficult to link the dominant channel-forming discharge to a specific recurrence interval, it seems that for a region like South Africa, river channels are formed by discharges that occur rather infrequently with recurrence intervals of between 5 and 20 years.

Box 8.2

Determination of the Effective Discharge (Dollar and Rowntree, 2003)

1. Use the daily flow record to generate a flow duration curve.
2. Divide the flow duration curve into flow classes as follows:
   - Nine 10% duration flow classes between the 99.99% equalled or exceeded flow percentile and the 10% flow percentile
   - One 5% duration flow class between the 10% equalled or exceeded flow percentile and the 5% flow percentile
   - One 4% duration flow class between the 5% equalled or exceeded flow percentile and the 1% flow percentile
   - One 0.9% duration flow class between the 1% equalled or exceeded flow percentile and the 0.1% flow percentile
   - One 0.09% duration flow class between the 0.1% equalled or exceeded flow percentile and the 0.01% flow percentile
3. Calculate the geometric mean of each flow class.
4. Calculate the sediment concentration for each flow class by means of sediment transport equations such as Engelund and Hansen (1967) or Yang (1973) and, in conjunction with the duration over which each flow class occurs, determine the sediment load.
5. Express the sediment load associated with each flow class as a percentage of the total sediment load and determine the effective discharge as the geometric mean of the flow class that transports the most sediment.

Regime theory

Regime theory attempts to establish the equilibrium relationships that exist within an alluvial river channel between a characteristic discharge, sediment characteristics, channel form and channel gradient. Alluvial rivers typically have three degrees of freedom, *viz*. channel width, depth and gradient, which are controlled by flow and sediment regimes. Whereas the discharge and sediment characteristics are usually known variables, channel width, depth and gradient need to be determined analytically. Three equations are therefore needed, of which two are generally available, i.e. a flow resistance equation and an equation defining sediment transport characteristics. However, a third equation is usually not readily available. Various approaches to overcome this problem have been developed and these may be classified into two broad categories, *viz*. empirical methods and rational (analytical) methods. Empirical methods rely upon experimental or field data for determining empirical relationships between a characteristic discharge and the variables defining channel dimensions and gradient, and as such, tend to be site or region specific. The inadequacy of the empirical methods in explaining the cause of the dynamic adjustment of rivers has prompted the development of the rational regime methods. Most rational methods can be classified as extremal methods, which are motivated by the conviction that a regime channel is formed because a certain physical quantity tends towards a minimum or maximum value (Yalin, 1992). Once the value is reached, the channel is 'in regime'. The following paragraphs provide a brief overview of existing regime equations and models that may be used for determining channel width, depth and gradient as well as the relationship between discharge and channel pattern. In addition, conceptual models related to the formation of macro-scale bed forms are also presented.

Channel width, depth and gradient

Over the last century, various regime equations, both empirical and analytical, have been developed. In general, most of the equations are of the same form and relate channel width (W) and channel depth (D) in metres and channel gradient (S) to one or more independent variables, *viz*. a characteristic discharge, sediment discharge or a characteristic bed particle diameter. Some equations also accommodate the effect of vegetation type found on the river banks. Table 8.3 lists some of the existing regime equations.

In an attempt to develop regime equations applicable to South African rivers, Beck and Basson (2003) calibrated equations for channel width and depth based on a large set of South African river data. This resulted in the following equations, which relate equilibrium width and depth to a discharge (m^3/s) with a return period of 10 years (Q_{10}) and channel gradient :

$$W = 2.488 Q_{10}^{0.357} S^{-0.230} \tag{8.11}$$

$$D = 0.085 Q_{10}^{0.377} S^{-0.153} \tag{8.12}$$

The above equations were verified with an independent data set and were found to accurately predict the channel geometry for relatively natural (unimpacted) rivers. However, in the case of rivers which have been drastically affected by a change in flow regime (due to the construction of a dam for example), the above equations proved inaccurate. Consequently, based on channel geometry data for 12 rivers downstream of dams, Beck and Basson (2003) calibrated the following equations, which yield very similar results, to determine the reduced average channel width after construction of a dam:

$$W_2 = -3.40 + 0.856\, W_1 + 0.142\, MAR_2 - 0.0013\, Q_{p1} \tag{8.13}$$

$$W_2 = -1.02 + 0.805\, W_1 + 0.183\, MAR_2 - 0.00036\, Q_{a1} \tag{8.14}$$

In these equations W_2 is the post-dam channel width (m), W_1 is the pre-dam channel width (m), MAR_2 is the post-dam MAR (m^3/s), Q_{p1} is the pre-dam highest flood peak (m^3/s), and Q_{a1} is the pre-dam mean annual maximum flood peak (m^3/s).

Table 8-3 Existing regime equations

Reference	Channel Width	Channel Depth	Channel Gradient	Equation Units	Comments
Chitale (1966)	$2.187Q^{0.523}$	$0.486Q^{0.341}$	$0.0005Q^{-0.165}$	**ft; ft^3/s**	Sand-bed rivers Predicts wetted perimeter and hydraulic radius instead of channel width and depth Q = dominant discharge
Kellerhals (1967)	$3.26Q_{bf}^{0.50}$	$0.182d_{90}^{-0.12}Q_{bf}^{0.40}$	$0.086d_{90}^{0.92}Q_{bf}^{-0.40}$	**ft; ft^3/s**	Q_{bf} = bankfull discharge d_{90} = 90th percentile bed particle size
Hey (1982)	$2.2Q_s^{-0.05}Q_{bf}^{0.54}$	$0.16d_{50}^{-0.15}Q_{bf}^{0.41}$	$0.68Q_s^{0.13}d_{50}^{0.97}Q_{bf}^{-0.53}$	**ft; ft^3/s**	Gravel-bed rivers Q_{bf} = bankfull discharge Q_s = sediment discharge d_{50} = 50th percentile bed particle size
Bray (1982)	$2.08d_{50}^{-0.07}Q_2^{0.53}$	$0.256d_{50}^{-0.025}Q_2^{0..33}$	$0.097d_{50}^{0.586}Q_2^{-0.334}$	**ft; ft^3/s**	Gravel-bed rivers Q_2 = two-year RI flood peak d_{50} = 50th percentile bed particle size
Hey and Thorne (1986)	$k_1 Q_{bf}^{0.5}$	$0.22Q_{bf}^{0.37}d_{50}^{-0.11}$	$0.087Q_{bf}^{-0.43}Q_s^{0.1}d_{50}^{-0.09}d_{84}^{0.84}$	**m; m^3/s**	Gravel-bed rivers Q_{bf} = bankfull discharge Q_s = sediment discharge k_1 = f (bank vegetation) d_{50} = 50th percentile bed particle size d_{84} = 84th percentile bed particle size
Yalin (1992)	$1.5\ d_{50}^{-0.25}Q_{bf}^{0.50}$	$0.15\ d_{50}^{-0.07}Q_{bf}^{0.43}$	$0.55\ d_{50}^{1.07}Q_{bf}^{-0.43}$	**ft; ft^3/s**	Gravel and cobble bed rivers Rational analysis
Julien and Wargadalam (1995)	$0.512Q^a d_s^{\beta} S^{\gamma}$ $\alpha = (2+4m)/(5+6m)$ $\beta = -4m/(5+6m)$; $\gamma = (-2m-1)/(5+6m)$	$0.2Q^a d_s^{\beta} S^{\gamma}$ $\alpha = 2/(5+6m)$ $\beta = 6m/(5+6m)$; $\gamma = -1/(5+6m)$	$12.4Q^a d_s^{\beta} S^{\gamma}$ $\alpha = -1/(3+2m)$ $\beta = 5/(4+6m)$; $\gamma = (5+6m)/(4+6m)$	**m; m^3/s**	Q = dominant discharge $m = 1 / \ln(12.2D/d_s)$, with $d_s = d_{50}$

Channel pattern

In addition to adjusting its shape and gradient, a river may also adjust its pattern in response to a modified flow and sediment regime. Channel pattern displays a close relationship to channel gradient, with 'gradient thresholds' defining the discontinuities between the three major channel patterns, *viz.* straight, meandering and braided. Under a particular flow regime, a change in channel gradient can therefore lead to a change in river pattern. Typical relationships between channel pattern, sinuosity and channel slope are as follows (Beck and Basson, 2003):

- Straight rivers have a sinuosity of less than 1.5 and generally occur on flat slopes with small width/depth ratios.
- Meandering rivers occur on steeper slopes with a sinuosity of more than 1.5 and increasing width/depth ratios.
- Braided rivers occur on even steeper slopes, with a decreasing sinuosity and even higher width/depth ratios.

The approach that has generally been adopted by researchers to predict the relationship between discharge and channel pattern entails the identification of a critical channel gradient, which defines the threshold between braided (steeper gradient) and meandering (flatter gradient) channel patterns. In most cases, the gradient is related to bankfull discharge in cu ft/s (Q_{bf}) or bankfull discharge and a representative bed particle size (ft):

Leopold and Wolman (1957):

$$S = 0.0125 Q_{bf}^{-0.44} \tag{8.15}$$

Henderson (1966):

$$S = 0.002 d_{50}^{1.15} Q_{bf}^{-046} \tag{8.16}$$

Beck and Basson (2003) used the same data set that was employed to calibrate equations (8.11) and (8.12), to determine the threshold gradient that separates braided and meandering channels as described by the following equation, with Q_{10} representing discharge (m^3/s) with a return period of 10 years:

$$S = 0.159\ Q_{10}^{-0.557} \tag{8.17}$$

Macro-scale bed deformation

Macro scale bed deformation typically involves the formation of pool-riffle or pool-rapid structures in gravel, cobble and boulder bed rivers. These bed forms have been described empirically by Leopold *et al.* (1964) and Hey and Thorne (1986), who found that riffle spacing in gravel-bed rivers is usually between 5 and 7 times the bankfull width. However, their findings were mostly based on observations in lower river reaches, which displayed a high degree of sinuosity, and were not representative of pool-riffle or pool-rapid sequences characteristic of middle and upper reaches.

Based on data collected in various Western Cape rivers, Jonker *et al.* (2002) investigated relationships between bed particle size, average channel gradient and various parameters which describe the geometry of macro-scale bed forms, including pool depth, bed form length, and local riffle gradient. They also proposed an analytical model to define the relationship between macro-scale bed form geometry and a characteristic discharge based on the hypothesis that the formation of pools and riffles is a mechanism of self-adjustment by a river towards obtaining dynamic equilibrium. Other conceptual models which have been proposed towards a fundamental understanding of the physical processes controlling macro scale bed deformation in gravel and cobble bed rivers are the antidune theory (Shaw and Kellerhals, 1977; Whittaker and Jaeggi, 1982; Chin, 1999), the dispersion and sorting theory (Yang, 1971) and the velocity reversal theory (Keller, 1971). However, it is important to note that none of the above theories have been conclusively verified with independent field or laboratory experiments.

8.3.3 Sediment flushing flows

Although natural phenomena such as catchment erosion may occasionally lead to excessive sediment being introduced and deposited on gravel and cobble river beds, natural floods ensure its periodic removal. The construction of a dam, however, leads to a change in flood peaks, flood frequency and sediment transport capacity in the river channel downstream. Fine sediments introduced into this part of the river system from the incremental catchment downstream of the dam or from the dam itself, may therefore accumulate in parts of the river bed (refer to Figure 8-4). In order to flush these unwanted fine sands from the interstitial spaces between the cobbles and gravels, special reservoir releases known as ‘flushing flows’ may be specified (Reiser *et al.*, 1989).

The range of effective flushing flows is relatively narrow. Whereas the rate and efficiency of fine sediment removal increases with discharge, so does the potential cost in the form of lost economic opportunity as the released water is lost from storage and subsequent use. The transport rate of larger-sized sediments and the potential for erosion also increase with discharge and may need to be kept within limits. The size of a flushing flow may be further constrained by the release capacity of the dam, financial and legal liabilities associated with the creation of an artificial flood as well as the availability of stored water at the appropriate time (Wilcock *et al.*, 1996).

Ecological significance

In gravel-, cobble- and boulder-bed rivers, many aquatic species are dependent on the interstitial spaces between the bed particles for their survival. Some fish species, for example, use these spaces for laying their eggs while the spaces also provide habitat and sheltering for various benthic insects and macro-invertebrates as well as storage space for trapped nutrients. In addition, algae, fungi and micro-organisms use the exposed surface area of cobbles as habitat. The accumulation of fine sediments in these rivers, which cover the large bed particles and fill the interstitial spaces, can therefore have a detrimental effect on the whole aquatic ecosystem.

Figure 8-4 Accumulation of fine sediment on the river bed (Wemmershoek River, Western Cape)

Flushing flow methodologies

Effective flushing flow strategies need to consider the magnitude, timing and duration of the flushing flow in order to allow for the entrainment and removal of fine sediments. Although there is a clear need to specify flushing flows as accurately as possible, relatively crude methods are often used for their determination due to a lack of appropriate models. Flushing flow methods can generally be classified into three categories, *viz*. hydrological, morphological and sedimentological methods (Gordon *et al.*, 1992).

Hydrological methods are based on an index obtained from flow records, such as a discharge with a certain return period or probability of exceedence, while morphological methods typically specify flushing flows as some proportion of bankfull flow or the effective discharge. Usually these methods are based on observations at the site of interest or in other similar channels and as such are empirical in nature.

The sedimentological methods on the other hand are physically based and require knowledge of channel form, gradient, sediment influx and substrate composition as well as sediment entrainment and transport theory. While the empirical flushing flow methods are based on experimental observations, the theoretically based models are mainly concerned with defining incipient motion conditions in mixed bed sediments and as such are subject to uncertainty due to the complexity of flow and sediment transport patterns in cobble-bed rivers. An attempt to develop a comprehensive flushing flow strategy for gravel-bed rivers based on sedimentological methods was made by Wilcock *et al.* (1996). They developed a basis for evaluating the trade-offs between discharge, flow duration and pool dredging which determine rates of bed mobilisation and sand removal. This involved the development of a set of simple functions representing sand and gravel transport, gravel entrainment, sub-surface sand supply and pool sediment trapping and the combination of these functions into a sediment routing algorithm to evaluate flushing alternatives for the Trinity River in California. They recommended a flow of moderate size, which limits gravel loss and maximises sand trapping by pools, from where the sand can then be removed by dredging. In another flushing flow study, O'Brien (1987) determined the flow needed to mobilise sand trapped within a cobble bed, based on flume studies and field data collected in the Yampa River in Colorado. From actual bed load measurements, sediment load-discharge relationships were developed and used to calculate the ‘effective’ discharge, which was then set as the peak of the flushing flow hydrograph.

The following paragraphs provide an overview of existing models which have been developed to determine flushing flows and include models based on shear stress, stream power as well as semi-empirical models.

Shear stress model

Based on the critical shear stress equation (equation (8.1)), Milhous and Bradley (1986) redefined the critical dimensionless shear stress as a 'stream substrate movement parameter' (β) for the estimation of flow that is needed for the flushing of fine sediments in a river, i.e.

$$\beta = \frac{RS_e}{d_{50a}(G_s - 1)} \tag{8.18}$$

where R is the hydraulic radius (m), S_e is the energy gradient, d_{50a} is the median particle diameter of the bed surface material (m), and G_s is the specific gravity of the bed particles.

Based on data obtained in Oak Creek, Oregon (Milhous, 1973), Milhous and Bradley found that the value of β required for the removal of fine sands from the surface of a gravel-bed river equals 0.021, while a β value of 0.035 is needed for the removal of fine material from within the substrate (depth flushing). The disadvantage of this method is that the proposed values of β are based on site-specific data.

Stream power model

In an attempt to provide a fundamental theoretical basis for the specification of flushing flows in terms of time and discharge dependent relationships, Jonker *et al.* (2002), with the aid of physical model experiments, developed a scour model to predict the maximum (equilibrium) depth of scour of fine sands in a cobble-bed river under certain hydraulic conditions (Box 8.3). The model is based on a stream power model developed by Rooseboom and Le Grange (1994) for describing the condition of dynamic equilibrium in a deformed sand-bed river. The scour model defines distinct relationships between absolute bed roughness (or maximum scour depth), sand particle characteristics and the relative applied power, with maximum scour depth based on average conditions within a cobble-bed area and defined as the level below the top of the cobbles at which no further scour is observed. Their results confirmed that at the point of maximum sand scour depth in a cobble-bed river, critical conditions for sediment movement prevail at and below an interface between a thin laminar boundary layer along the bed and turbulent eddies above (see Figure 8-5). By equating the power required to suspend sand particles under laminar boundary conditions to the turbulent power being applied along the bed, Le Grange (1994) derived equation (8.19) to define the condition of scour equilibrium, or maximum depth of scour in a cobble bed.

$$\frac{\sqrt{gDs}}{V_{ss}} = \left[\frac{\sqrt{gDsk}}{\sqrt{2\pi\nu}}\right]^{1/2} Constant \quad \left[\frac{\nu}{\sqrt{gDsd}}\right] \tag{8.19}$$

In this equation g is gravitational acceleration (m/s^2), D is the flow depth (m), s is the energy gradient (≈ channel gradient), V_{ss} is the settling velocity of sand particles under viscous conditions (m/s), k is the absolute bed roughness (= scour depth) (m), ν is the kinematic viscosity (m^2/s), and d is the median sand particle diameter (m).

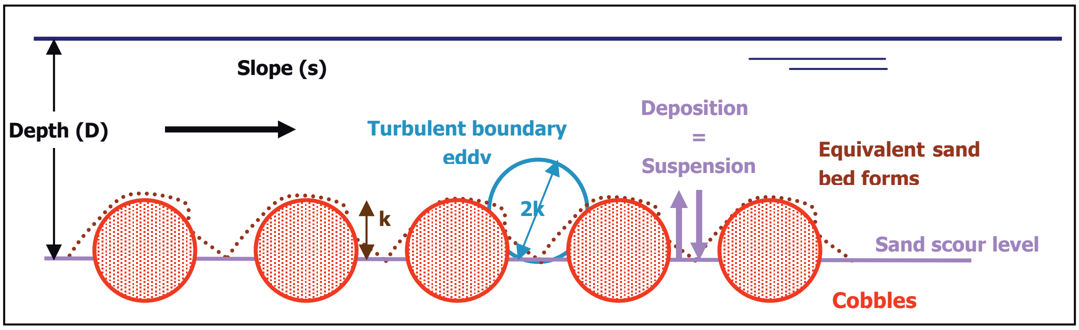


Figure 8-5 Schematic representation of the Jonker *et al*. (2002) sand scour model

Although equation (8.19) provides a practical methodology for estimating the maximum depth of scour in cobble-bed rivers, cognizance should be taken of the fact that, at this stage, the model has not been applied in practice. Furthermore, the model is based on uniform cobble sizes and the results would have to be adjusted to allow for the impact of non-uniform cobble sizes. Finally, it should be noted that the physical model experiments which were used to calibrate the cobble-bed sand scour model, were conducted under clear water conditions. This would be representative of flushing conditions immediately downstream of dams. However, as the distance from the dam increases and more and more sediment is entrained and transported, the Δ-values as calibrated during the experimental results might not be applicable.

A shortcoming of the Jonker *et al.* (2002) model relates to the absence of time-dependent relationships, which are critical for quantifying the duration of a flushing flow in order to ultimately determine the volume of flushing water to be released from a dam. To address this problem, Hirschowitz *et al.* (2007) developed a semi-empirical, equilibrium state model, which allows the time (T_A) required for sand scour down to a certain absolute depth below the top of the cobbles at a particular longitudinal section along a cobble bed to be determined as

$$T_A = T_S + DP * L \tag{8.20}$$

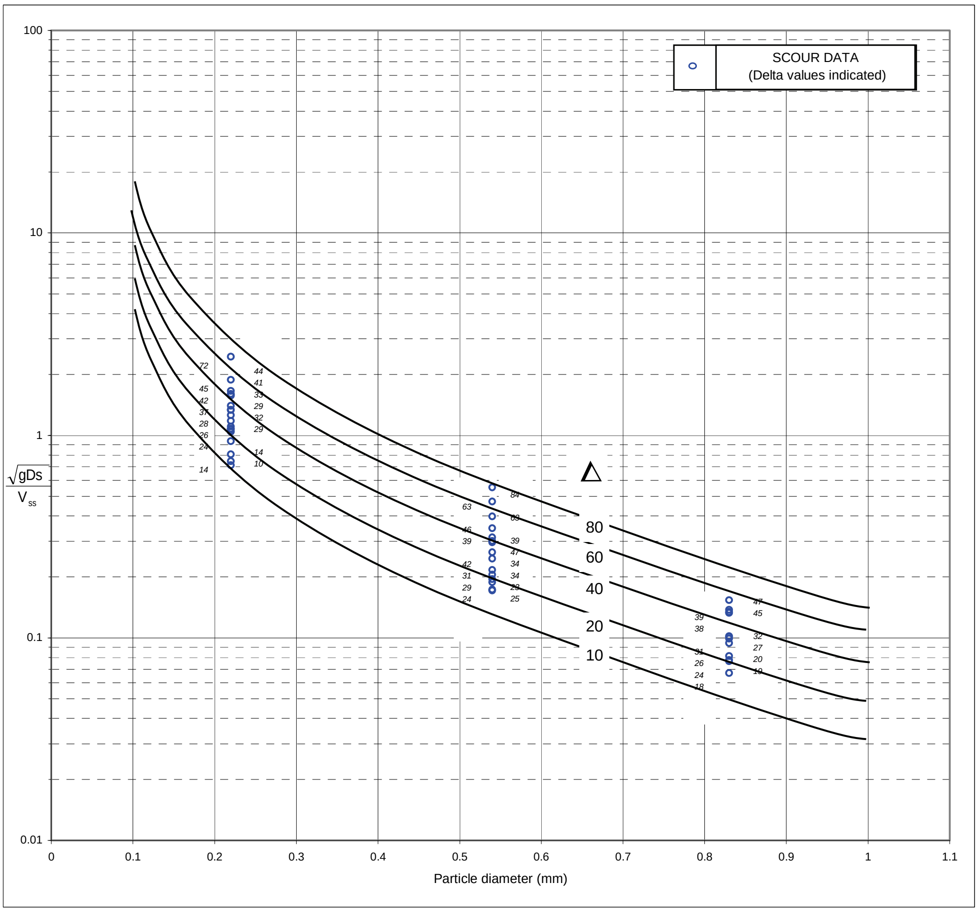
in which T_S is the time required to reach a specified scour depth at the upstream section, DP is the rate of downstream progression of scour, and L is the distance from upstream section of scour area to area under concern.

Box 8.3

Estimation of Maximum Scour Depth in Cobble-bed Rivers (Jonker *et al.*, 2002)

In order to calibrate the relationship as expressed by equation (8.19), Jonker *et al.* (2002). used experimental results to develop the diagram as shown below. This diagram enables the discharge that is required to obtain a certain absolute depth of sand scour in a cobble bed to be calculated through an iterative procedure, which involves the following five steps:

1. For the required absolute depth of sand scour (k), estimate a discharge and, using the Chézy equation, calculate the corresponding flow depth (D) based on channel geometry and gradient (s).
2. Calculate the relative applied power ($\sqrt{gDs}/V_{ss}$).
3. Based on the sand particle diameter and the value of $\sqrt{gDs}/V_{ss}$, read off a value of Δ .
4. Calculate the value of $\Delta = \left(\sqrt{gDsk}/\sqrt{2\pi v}\right)^{0.5}$, and compare to the value in Step 3.
5. If the Δ-values in Step 3 and 4 are different, re-estimate a discharge and repeat Steps 1 to 4 until the Δ-values are equal.



In order to solve equation (8.20), Hirschowitz *et al.* developed several semi-empirical relationships based on experimental results. In essence, the equations define relationships between time of scour (T_S), rate of progression of scour (DP), applied bed shear stress (τ), median sand particle diameter (d_{50}), average flow velocity (V), cobble diameter (D_{cobble}) and required scour depth (SD) as follows (Figure 8-6):

$$T_S = t_c . \ln\left(ESD / \left(ESD - SD \right) \right) \tag{8.21}$$

$$DP = (0.0155\theta - 0.0019)V \tag{8.22}$$

with t_c (a time constant) defined by

$$t_c = \frac{2815\, D_{cobble}}{V(\theta - 01545)^{0.737}} \tag{8.23}$$

in which θ is the Shields parameter, or dimensionless critical shear stress (equation (8.1)) in terms of d_{50}, and ESD is the equilibrium scour depth, which is the smaller of $(358\ \theta)d_{50}$ or $(0.86\ D_{cobble}.)d_{50}$.

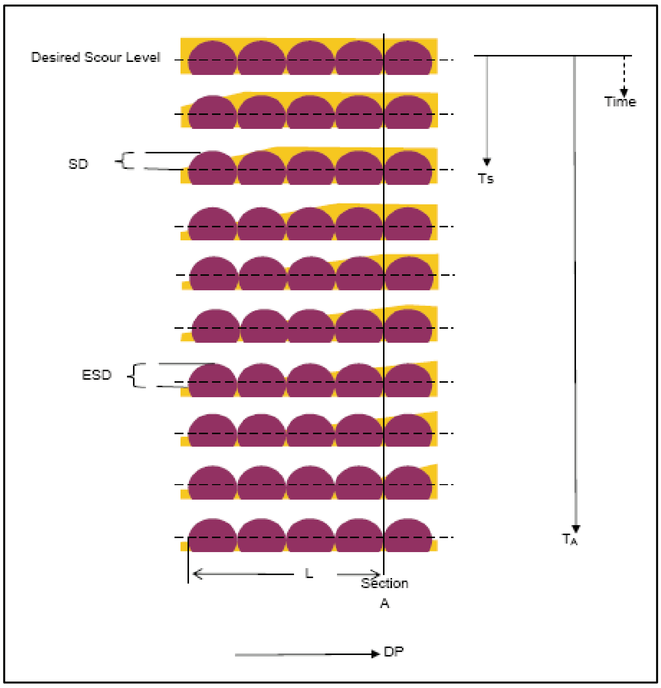


Figure 8-6 Diagrammatic illustration of the Hirschowitz *et al.* (2007) sand scour model

In applying the Hirschowitz *et al.* model to estimate the maximum depth of scour in cobble-bed rivers, cognisance should be taken of the fact that the time *versus* scour depth relationships that were developed were based on fully embedded cobbles at the initiation of each experiment, while scour was assumed to start at the upstream end of the area of interest and to progress downstream at a constant rate, irrespective of localised channel geometry. Furthermore, the experiments made use of uniform cobble sizes while scour depths were limited to 0.86 times the cobble diameter.

8.4 Conclusion

Changes to channel morphology (channel form and substrate) affect aquatic habitat, as the response of the instantaneous discharge to channel form and substrate determines ecosystem functioning through the availability of physical (hydraulic) habitat for aquatic species. Within this context, this Chapter presented hydraulics-based models and techniques that are applicable within an ecohydraulics context and which are aimed at quantifying those components of the flow regime that are important for maintenance of channel form and substrate. Flow components specifically addressed include bed disturbance flows, which concern the initiation of movement of individual bed particles, channel maintenance flows, which determine channel form and gradient and sediment flushing flows, which are aimed at ‘flushing’ or removing fine sediments from the interstitial spaces between larger bed particles. Cognizance should be taken of the fact that many of the models presented in this Chapter, emanate from research studies and have not been applied in practice. Caution should therefore be exercised when applying these models, specifically where field conditions vary significantly from the controlled experimental environment under which models were often calibrated. Furthermore, it is important to note that these models are essentially theoretically based and should not be confused with the so-called habitat-hydraulic models (e.g. RHYHABSIM (Jowett, 1989)), which combine biological data of indicator species with the hydrological, hydraulic and morphological characteristics of a river to produce a quantifiable relationship between flow and usable habitat area.

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Notation

a: coefficient in critical shear stress relationship
b: exponent in critical shear stress relationship
b: exponent in critical dischare relationship
D: flow depth
D: channel depth
D_{cobble}: cobble diameter
DP: rate of downstream progression of scour
d: particle diameter
d: median sand particle diameter
d_i: diameter of particle under consideration
d_r: reference particle size
d_{16}: 16th percentile particle size
d_{50}: median particle diameter
d_{50a}: median particle diameter (bed surface material)
d_{84}: 84th percentile particle size
d_{90}: 90th percentile particle size
ESD: equilibrium scour depth
G_s: specific gravity of bed particles
g: gravitational acceleration
k: absolute bed roughness = scour depth
k_1: coefficient in regime equation
L: distance from upstream section of scour area to area under concern
MAR_2: post-dam MAR (mean annual runoff)
m: factor in regime relationship
Q: discharge
Q: dominant discharge
Q_{a1}: pre-dam mean annual maximum flood peak
Q_{bf}: bankfull discharge
Q_{p1}: pre-dam highest flood peak
Q_s: sediment discharge
Q_2: 2-year RI flood peak
Q_{10}: 10-year RI flood peak
q_{cr}: critical water discharge per unit width for uniform particle size bed
q_{ci}: critical water discharge per unit width for movement of particle d_i
R: hydraulic radius
RBS: Relative Bed Stability
Re^*: roughness Reynolds number
S: channel gradient
s: energy slope

s: channel gradient

s: energy gradient ≈ channel gradient

S_e: energy gradient

T_A: time required for sand scour to specified depth

T_S: time required to reach a specified scour depth at the upstream section

t_c: time constant

V_{ss}: settling velocity

V^*: shear velocity

W: channel width

W_1: pre-dam channel width

W_2: post-dam channel width

α: exponent in regime relationship

β: exponent in regime relationship

β: critical dimensionless shear stress parameter

β: stream substrate movement parameter, critical dimensionless shear stress

γ: exponent in regime relationship

Δ: dimensionless parameter representing absolute sand scour depth

θ: dimensionless shear stress parameter

θ_c: dimensionless critical shear stress parameter

ρ_s: sand density

ρ: water density

τ_b: average boundary shear stress

τ_c: critical shear stress

ν: kinematic viscosity of water

9. THE ROLE OF ECOHYDRAULICS IN THE SOUTH AFRICAN ECOLOGICAL RESERVE

AL Birkhead

9.1 Introduction

Changing the natural hydrology of river systems to provide water for human needs, coupled with modified land-use, has resulted in a worldwide trend of deteriorating river ecosystem health. This has spurred the development of the science of environmental flow assessment (EFA), which has become internationally recognised as the means for assessing the quality and quantity of flow required for sustainable use of riverine ecosystems.

The prediction and mitigation of impacts to river systems are components of environmental impact assessment (EIA), EFA and river rehabilitation. Environmental impact assessments predict the impacts of proposed change, evaluate alternative options and provide measures for the mitigation of impacts. Environmental flow assessments determine the magnitude and timing of flows necessary to maintain the river ecosystem in a certain condition (which may be an improved state), whereas river rehabilitation deals with returning (through broader means) aspects of ecological function to a degraded system, as discussed in Chapter 10: River Rehabilitation and Impact Mitigation Structures. As environmental flow requirements (EFRs) are associated with different river states, and describe the impacts on river condition from different flow management options, it is appropriate to include their estimation in EIAs as Specialist Studies, thereby informing the EIA process and outcomes. Alternatively, an EFA can be recommended in an EIA. Similarly, an EFA should form part of the river rehabilitation process. Environmental impact assessments, EFRs and river rehabilitation are all aspects of Integrated Water Resource Management (IWRM).

Environmental flow assessments also provide the means for predicting the consequences of our actions on ecosystem health or ecological status. Determinants of river ecological status include abiotic drivers (physical and chemical) and biological responses. Physicochemical drivers include the temporal and spatial distribution of river flow, which is the fundamental management variable (Dollar *et al.*, 2007; Poff *et al.*, 1997; Walker *et al.*, 1995), water chemistry, and river form or morphology (Figure 9.1). River morphology, in turn, depends on catchment geology, land-use and hydrology (all of which influence sediment supply), hydraulics and vegetation, and determines the physicochemical template for biological processes. Changes in natural flow and sediment regimes of rivers may be due to changes in land-use, the construction of impoundments, flow abstractions (including groundwater) and return flows. In-channel structures (e.g. impoundments, structures for abstractions and return flows, flood and bank protection, construction of artificial habitats) also alter the flow and sediment regimes, but these may have more localised influences depending on their scale. Riverine vegetation both responds to and influences flow and sediment behaviour, resulting in a feedback relationship between vegetation, flow and river morphology (Nicolson, 1999; and James *et al.*, 2001, 2002). Biota respond to discharge through local hydraulic conditions, such as depth, velocity and inundated area. It is therefore necessary to understand how these flow variables are related, so that management of drivers provides the required ecologically relevant hydraulic habitat. Ecohydraulic analysis is therefore a crucial part of environmental river management. In South Africa, this is undertaken within the context of the Ecological Reserve for rivers (termed Ecological Reserve (ER) or Reserve in the following sections).

The focus in this chapter is on the expression of discharge using ecologically relevant local hydraulic parameters (i.e. the green linkages in Figure 9.1), under the influences of river morphology (including the substrate conditions) and vegetation, i.e. the blue linkages in Figure 9.1. This assumes a time scale sufficiently short that morphology and vegetation states can be considered fixed, and flow as steady. The longer-term influence of hydraulics on channel form is considered in Chapter 8: Channel Maintenance flows. The interaction between vegetation and channel form is beyond the scope of this report, although it is an important consideration in long-term river management and planning rehabilitation strategies (Chapter 10).

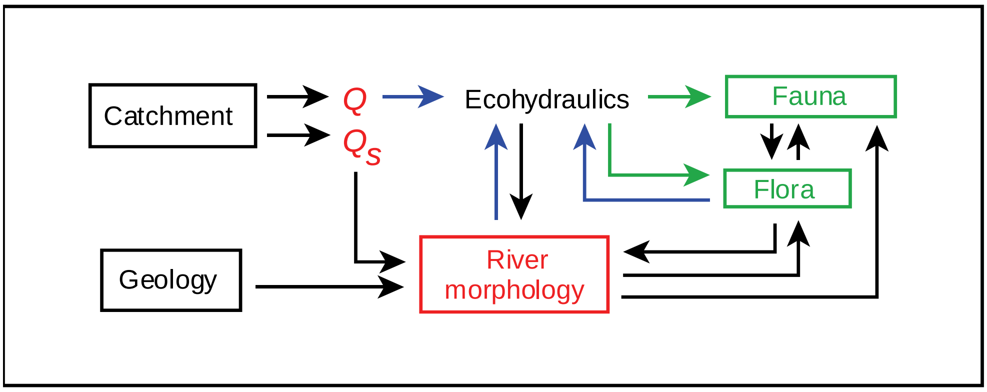

Figure 9-1 The causal links governing ecohydraulics in the South African Ecological Reserve, modified from James *et al.*, 2001 (Q = discharge; Q_S = sediment supply; red and green text indicate drivers and biological responses, respectively)

9.2 The South African Ecological Reserve for rivers

9.2.1 Background

South Africa has recognised the importance of protecting river ecosystems through the National Water Act (NWA, No. 36 of 1998). This protection of water resources relates to their use, development, conservation, management and control (NWA, 1998). This is explained in the NWA as the recognition of our responsibility to protect the ability of water resources to sustain long-term utilisation, which requires protection of the structure, integrity and function of aquatic ecosystems (MacKay, 1999a). The Act protects water resources by ensuring provision of a requirement known as the 'Reserve'. This consists of two parts – the Basic Human Needs Reserve (BHNR) and the ER. The BHNR provides for the essential requirements of individuals served by the water resource and includes water for drinking, food preparation and personal hygiene (25 to 60 ℓ/person/day). The aims of the ER are stated in two ways: either maintenance of the river ecosystem in a certain state (the ecological status, or eco-state), or limiting the risk of irreversible ecosystem damage to a given level. The second of these objectives is explained by MacKay (1999a) as the desire to prevent unintentional exceedance of the limits of sustainable utilisation, and this is recognised as a cornerstone of the policy of protection. An underlying assumption is that these two aims are related, with the degree of modification from reference conditions (physical and biological) taken to be related to the risk of irreversible degradation of resource quality (MacKay, 1999b).

The requirements of the original EFAs in South Africa were termed Instream Flow Requirements (IFRs). This term is no longer used because it implies that only the instream component is considered (i.e. excluding riparian). The current terminology in South Africa is the 'Ecological Water Requirement' (EWR) which is used in preference to the internationally accepted term 'environmental flow requirement' (EFR) because the term 'flow' is deemed to disregard water quality considerations, and because 'ecological' refers specifically to this component of the environment and excludes social aspects. In South Africa, an EWR is regarded as a Preliminary Ecological Reserve once it is ratified by the Minister of the Department of Water Affairs and Forestry (DWAF). It remains 'Preliminary' until such time as the river is classified and gazetted using the Water Resource Classification System (WRCS), whence it becomes established as a Reserve. The WRCS (Dollar *et al.*, 2006) is used to determine water resource Management Classes, which are composite statements of environmental, social and ecological aspects of the resource. The final ER is therefore expressed as a Management Class and is set to maintain a certain state of ecological river health.

The terms Reserve or Ecological Reserve are often loosely used, and may be taken to actually mean an EWR prior to its ratification and implementation. Within this local context, 'Ecological Water Requirement' is the term used in this chapter. Furthermore, to avoid unnecessary repetition, 'Reserve' and 'Ecological Reserve' both imply Ecological Reserve (ER) for rivers, and 'flow assessment' denotes 'ecological flow assessment for rivers'.

The ER is considered in terms of flow magnitude (flow rate or discharge) and its temporal aspects (frequency, duration, timing, and rate of change). Temporal flow variations include both seasonal variations of base flow and high flows or events (which include floods). Allowance is made for these within the Reserve output: it is standard practice, and a requirement of the Resource Directed Measures (RDM) Directorate of DWAF, that all Reserve determination methods generate the so-called 'assurance rule tables' (Hughes *et al.*, 2007). Table 9.1 provides an example of assurance rules, with the monthly flows expressed according to their temporal exceedance. Assurance rules are necessary for planning water resource allocation using hydrological modeling at a catchment-scale, and are associated with an ecological state or category. The Ecological Category (EC) defines the ecological river condition in terms of the deviation of biophysical components from the natural reference condition, expressed from A to F, with A being the closest to natural. Two tables of recommended flows are provided (Table 9.1): the first includes both the low and high flow components of the Reserve, and the second includes only the low flows. It is also common practice to specify the flow duration table of the natural flow regime used in the Reserve assessment. Management of EWRs for low flows is through assurance rules, and for high flows by other means (refer to Chapter 3 in Hughes *et al.*, 2007).

Studies of the association between the occurrence of water in the environment and ecological entities and processes (ecohydrology) are served through two paradigms (James and Thoms, 2007). Hydroecology is applied at the catchment level and focuses on the responses of organisms to temporal flow variations, such as fish-spawning stimulation. Ecohydraulics is applied at the river reach level and focuses on the manifestation of discharge as ecologically relevant local hydraulic conditions. The relationship and reconciliation between the approaches are discussed by James and Thoms (2007). Usually, ER flows are derived through ecohydraulic approaches, using steady-state hydraulic analyses of the relationships between discharge, hydraulic determinants of habitat (e.g. depth, velocity and inundated area), and the habitat requirements of the biota and plants (refer to Box 2.1).

Table 9-1 Example of assurance rule tables from an Ecological Reserve determination expressed as mean monthly flow (m^3/s)

Month	Temporal exceedance (%)									
	10	20	30	40	50	60	70	80	90	99
Reserve flows										
Oct	0.165	0.165	0.163	0.160	0.155	0.142	0.123	0.103	0.071	0.045
Nov	0.409	0.408	0.403	0.394	0.377	0.320	0.293	0.197	0.130	0.066
Dec	0.545	0.542	0.536	0.524	0.501	0.426	0.370	0.299	0.183	0.090
Jan	0.616	0.581	0.549	0.516	0.479	0.417	0.359	0.278	0.183	0.115
Feb	1.402	1.275	1.033	0.674	0.583	0.525	0.463	0.389	0.319	0.180
Mar	0.621	0.587	0.555	0.524	0.488	0.427	0.370	0.286	0.188	0.116
Apr	0.373	0.372	0.369	0.362	0.349	0.325	0.284	0.224	0.152	0.099
May	0.215	0.215	0.213	0.210	0.204	0.191	0.170	0.139	0.100	0.071
Jun	0.170	0.170	0.169	0.166	0.161	0.152	0.136	0.111	0.080	0.058
Jul	0.144	0.144	0.144	0.142	0.138	0.131	0.117	0.097	0.071	0.052
Aug	0.119	0.119	0.118	0.117	0.114	0.105	0.097	0.082	0.070	0.056
Sep	0.104	0.104	0.103	0.102	0.099	0.093	0.085	0.072	0.056	0.040
Reserve flows without high flows										
Oct	0.130	0.129	0.128	0.126	0.122	0.115	0.103	0.085	0.063	0.045
Nov	0.232	0.231	0.228	0.223	0.214	0.197	0.168	0.128	0.079	0.045
Dec	0.301	0.300	0.297	0.290	0.279	0.258	0.224	0.176	0.119	0.078
Jan	0.366	0.364	0.360	0.352	0.337	0.312	0.271	0.213	0.147	0.099
Feb	0.455	0.453	0.448	0.439	0.421	0.390	0.339	0.265	0.179	0.117
Mar	0.371	0.370	0.366	0.359	0.345	0.320	0.279	0.220	0.150	0.100
Apr	0.310	0.309	0.307	0.301	0.291	0.271	0.239	0.191	0.134	0.092
May	0.215	0.215	0.213	0.210	0.204	0.191	0.170	0.139	0.100	0.071
Jun	0.170	0.170	0.169	0.166	0.161	0.152	0.136	0.111	0.080	0.058
Jul	0.144	0.144	0.144	0.142	0.138	0.131	0.117	0.097	0.071	0.052
Aug	0.119	0.119	0.118	0.117	0.114	0.105	0.097	0.082	0.070	0.056
Sep	0.104	0.104	0.103	0.102	0.099	0.093	0.085	0.072	0.056	0.042
Natural duration table										
Oct	0.414	0.310	0.224	0.172	0.161	0.142	0.123	0.105	0.071	0.045
Nov	3.495	1.605	0.702	0.505	0.424	0.320	0.297	0.197	0.139	0.081
Dec	4.906	2.300	1.654	0.754	0.579	0.426	0.370	0.299	0.183	0.090
Jan	5.884	3.065	1.572	0.866	0.571	0.441	0.418	0.362	0.291	0.168
Feb	6.572	2.778	1.033	0.674	0.583	0.525	0.463	0.389	0.322	0.203
Mar	3.379	1.344	0.769	0.560	0.534	0.452	0.396	0.306	0.265	0.164
Apr	1.300	0.660	0.571	0.494	0.405	0.343	0.313	0.255	0.189	0.116
May	0.497	0.399	0.336	0.302	0.261	0.217	0.194	0.168	0.142	0.071
Jun	0.340	0.285	0.235	0.212	0.201	0.177	0.154	0.123	0.112	0.069
Jul	0.276	0.239	0.198	0.179	0.161	0.142	0.127	0.108	0.097	0.063
Aug	0.217	0.187	0.157	0.134	0.123	0.105	0.097	0.082	0.078	0.056
Sep	0.201	0.154	0.135	0.127	0.104	0.093	0.085	0.073	0.062	0.042

9.2.2 The levels of Ecological Reserve determination

South African policy recognises that Reserve determination studies undertaken in different situations will be conducted at different levels, both in terms of resources allocated and degree of uncertainty (or, using Reserve terminology, 'confidence') in the results. The level of determination depends on a number of factors, including the degree to which the catchment is utilised, the ecological importance and sensitivity of the river, the potential impact of proposed future water use (McKay, 1999a) and the availability of information.

The levels of ER assessment include the Desktop, Rapid, Intermediate and Comprehensive methods, in order (generally) of increased confidence. The Desktop method (Hughes and Münster, 2000) has a largely hydrological basis, utilising results from previous studies (initially IFRs and later EWRs) to relate flow recommendations associated with ecological river conditions to hydrological characteristics. As such, geomorphological, hydraulic and ecological considerations (as applied in previous flow assessments) are implicit in the Desktop method, albeit through a largely empirical approach. The Desktop and Rapid Level I methods, unlike higher levels of determination, do not directly utilise hydraulic information. Rapid assessments are divided into three sub-levels, namely I, II and III, with all levels using the standard Desktop flow estimate as a starting point. Level I requires a more accurate assessment of river condition than generally used in the standard Desktop method. Level II requires, in addition to this, measurements of discharge and depth, and a qualitative assessment of available habitat for flow indictor biota. This provides some means of ground-truthing the Desktop estimate, which may consequently be adjusted. Over and above these inclusions, Level III involves the collection of limited topographical, hydraulic and biophysical information. All Rapid determinations involve assessments of Desktop-generated estimates, mainly for low-flows (base-flows). Desktop-generated EWRs are specified as monthly flow volumes which may be expressed as mean monthly discharge (Table 9.1). It is therefore difficult to assess the adequacy of the high flows without determining the events required (magnitude, duration, timing and frequency). Rapid methods are envisaged as quick, low-cost assessments for 'small-scale' water-use applications that do not impact substantially on high flows. Higher Reserve levels (i.e. Intermediate or Comprehensive) are appropriate for assessing high flow ecological requirements.

From a hydraulics perspective, the main difference between Rapid III, Intermediate and Comprehensive levels is the amount of hydraulic and habitat data collected at sites. Additional information and more rigorous hydraulic analyses may be appropriate for more detailed studies (i.e. Intermediate and Comprehensive). Essentially, hydraulic results are similar, but with different level of uncertainty.

9.2.3 Ecological Reserve methods

An overview of environmental flow methodologies is provided by Tharme (2000), grouping the majority of the methodologies into four reasonably distinct categories: hydrological, hydraulic rating, habitat simulation and holistic. Hydrological methods rely largely, and often solely, on the use of measured or simulated flow data, and include the Tenant (or Montana) method, flow-duration curve analysis, and the South African Desktop method (Hughes and Münster, 2000). Hydraulic rating methods use hydraulic variables such as flow depth or wetted perimeter as surrogates for determinants of habitat to develop a relationship between habitat and discharge from which to derive flow recommendations, e.g. the Wetted Perimeter Method (Loar *et al.*, 1986). Habitat simulation methodologies attempt to assess flows on the basis of biotic responses at the level of instream habitat (Tharme, 2000), and include the Instream Flow

Incremental Methodology (IFIM) – the most commonly used environmental flow methodology worldwide. The IFIM focuses on evaluating the area of suitable habitat for particular species or life stages (refer to Section 3.5), and has been developed in conjunction with the Physical Habitat Simulation Model (PHABSIM). In holistic methodologies, important and/or critical flow components are identified in terms of criteria such as flow magnitude and timing, for all attributes of the riverine ecosystem. Tharme (2000) listed nine internationally recognised holistic methodologies, two of which were developed in South Africa, *viz*. the Building Block Methodology (BBM) and the Downstream Response to Imposed Flow Transformations method (DRIFT). More recently, the Flow Stressor-Response (FS-R) method was developed under the auspices of the Water Research Commission (WRC) (O'Keeffe and Hughes, 2004). These three methodologies (BBM, DRIFT and FS-R) represent considerable advancements from the first approaches used in South Africa, *viz*. the ‘Cape Town’ and ‘Skukuza’ methods, where water depths required for different ecological processes were identified and translated into discharge requirements (for a description, refer to King and O'Keeffe, 1989).

The BBM is based on the premise that certain flows within the hydrological regime of a river are more important than others for maintenance of the river ecosystem, and that these flows can be identified and described in terms of their magnitude, duration, timing and frequency (Tharme, 2000). These flows are the ‘building blocks’ of a modified flow regime for both maintenance and drought conditions, and in combination with high flows constitute the EWR associated with an EC.

A variation of the BBM is the Flow Management Plan (FMP). This was developed in South Africa for specific use in highly regulated and modified river systems, with specific reference to the flow-regulated Fish and Sundays Rivers in the Eastern Cape Province. The FMP was subsequently only applied to the Vaal River in the late 1990s. Since then, the F-SR approach was developed to include the evaluation of different flow management options (or scenarios), and resulted in the FMP becoming redundant. The BBM and FMP have been effectively replaced by DRIFT and FS-R as ecological flow assessment methods recognised by the RDM Directorate of the DWAF.

Like other holistic approaches, DRIFT is essentially a data-management tool, allowing data and knowledge to be used to their best advantage in a structured process (King *et al.*, 2003). It consists of four modules, namely biophysical, socio-economic, scenario and economic. In the biophysical module, the river ecosystem is described, and predictive capacity developed on how it would change with flow. The biophysical disciplines typically involved in a DRIFT (or FS-R) application are hydrology, hydraulics, water chemistry, fluvial morphology, botany, ichthyology and invertebrate zoology.

The FS-R method uses an index to score flow-related stress, to guide the evaluation of the ecological consequences of modified flow regimes (O'Keeffe *et al.*, 2002; O'Keeffe and Hughes, 2004). The ‘stress’ response of biota to different flows is determined through an assessment of habitat conditions at these flows. The original FS-R method has been extended to the Habitat Flow Stressor Response approach, with ecologically relevant hydraulic habitat (e.g. depth, velocity, inundated substrate and vegetation) being interpreted in terms of its usefulness to biological habitat requirements. The method may therefore be more explicitly termed ‘HFSR’.

Fundamentally, the hydraulic requirements of these South African developed holistic methods (i.e. DRIFT and HFSR) are identical, and involve the characterisation of the discharge-related, ecologically relevant hydraulic habitat for sites along river systems. Traditional methods of hydraulic data collection and analysis have evolved over the past two decades to meet this need, in parallel with the development and refinement of the flow assessment methods. The current role of ecohydraulics in the South African ER is described in the following section.

9.3 Ecohydraulics within the South African Ecological Reserve

9.3.1 Background

The role of hydraulics in the BBM, at the Comprehensive level of assessment, was first described by Rowlston *et al.* (2000). This had already been extended by Birkhead (1999) to include the description of hydraulics for Intermediate Reserve levels, since much of the material is equally applicable to different levels requiring hydraulic information (*viz.* Rapid Level III and higher determinations). These publications describe the role of hydraulics in terms of the sequence of activities involved, minimum and ideal (field) data, results, the specialist meeting (or workshop) where EWRs are determined, the terms of reference for an EWR, specialist training, potential pitfalls, developments and monitoring. A WRC study undertaken by Jordanova *et al.* (2004) dealt with further improving the role of hydraulics in the Reserve, with the following contributions: the development and testing (experimental and field) of new resistance equations that distinguish between the influences of small-, intermediate- and large-scale roughness (these are described in Chapter 7: Flow Resistance in Rivers), the use of three-dimensional (3-D) spatial representation modeling coupled with uniform and non-uniform one-dimensional (1-D) hydraulic analyses, the use of empirical frequency distributions for predicting the diversity of cross-sectional depth-averaged velocity, and the use of flow classes for defining ecologically relevant hydraulic habitat for fish and macro-invertebrates (hereafter referred to as ‘invertebrates’). A more recent WRC project on ecohydraulic modeling methods for South African rivers (Hirschowitz *et al.*, 2007) includes a review of findings and issues generated by previous research, development of methods for ecohydraulic assessments, and application of the methods to case studies. Some of these contributions are discussed further in Sections 9.3.4 and 9.3.5.

9.3.2 Reserve levels, site character, field information, analysis and uncertainty

As explained above, the role of hydraulics changes little with Reserve level (Rapid III and higher assessments) as all holistic methods requiring site-specific assessments need basic hydraulic information. This information is provided by a set of relationships between discharge, stage or maximum flow depth, velocity (average cross-sectional) and area of inundation[3]. For a topographical cross-section at a river site, area of inundation is expressed as cross-channel width and wetted perimeter[4]. Basic hydraulic information is obtained through the collection of different amounts of field data, and by applying different methods of analysis. Differences in approach have implications for the (hydraulic) uncertainty associated with the results, and ecohydraulic applications for the Reserve therefore require appreciation of the interdependence between data collection, method of hydraulic analysis, site characteristics, and uncertainty.

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[3] These relationships are termed ‘hydraulic ratings’ when considering the various EFA methods (refer to Section 9.2.3), but for the purpose of this document, ‘hydraulic rating’ refers specifically to the relationship between discharge and water level (or stage).

[4] Wetted perimeter is the tortuous cross-channel distance measured over the bed substrate.

Box 9.1

Rating functions and data

A rating function refers to the relationship between water level at a point along a river relative to an elevation datum (termed ‘stage’) and a discharge. Maximum water depth (stage relative to the lowest bed elevation across the channel bed) may also be used. A rating point or value denotes a stage-discharge co-ordinate. In hydraulic applications, discharge is the independent (management) variable, usually plotted on the horizontal (x) axis.

Rating functions are also used in a hydrological context to relate stage measured at gauging weir (or rated cross-section) to discharge. Here, stage is the independent variable, usually plotted on the vertical (y) axis.

These relations are illustrated graphically in Figure 9.2, which shows the influences of data collection (specifically the number of field surveys), type of (hydraulic) analysis, and hydraulic character of the river site on the specification of the Reserve level. The specific data requirements and methods of hydraulic analysis appropriate for the different levels are listed in Table 9.2, and described in Sections 9.3.3 and 9.3.4, respectively.

The graphic in Figure 9.2 may be interpreted as follows:

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

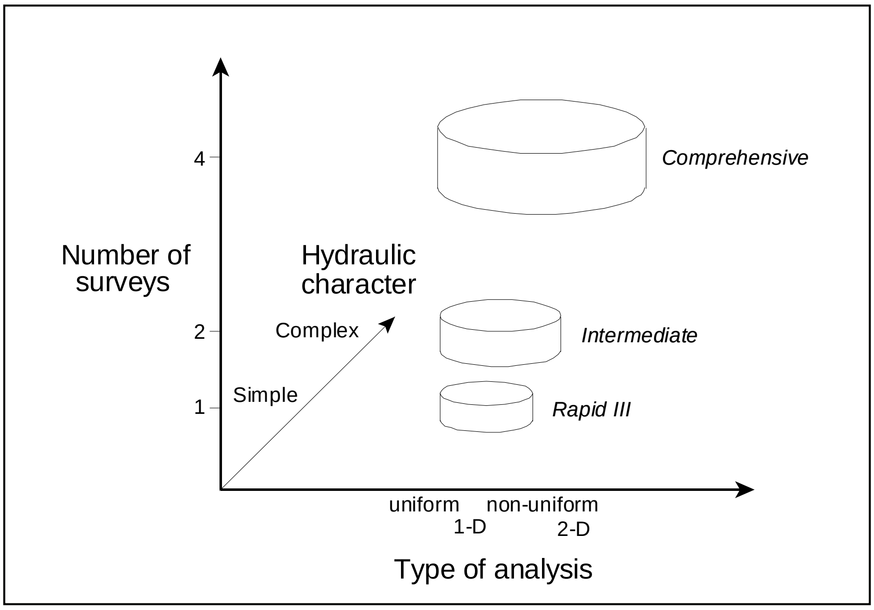


Figure 9-2 Relations between Reserve level, number of surveys, site character and type of hydraulic analysis

The basic hydraulic field data for any holistic Reserve assessment requiring explicit hydraulic information include the following: a cross-sectional survey; a low-flow measured rating (the low-flow measurement is essential, since high flows can generally be modelled more accurately than low flows in rivers with large bed roughness typical of EWR sites); water surface slopes; spatial distributions of depth and depth-averaged velocity; the substrate composition; and the position of marginal vegetation relative to the river topography. Uniform flow is generally assumed (i.e. equal longitudinal energy, water surface and channel bed gradients), and a resistance equation (e.g. Manning, Cheźy or Darcy-Weisbach, as described in Chapter 7) is typically used to synthesise an additional rating point for high flows. Sites should be selected and cross-sections located to support, as far as possible, the uniform flow assumption. Measured and modelled rating points are used to model a continuous rating function (refer to Section 3.3.1 and Figure 9.8). The rating function and cross-sectional geometry are then used to predict the relationships between discharge and ecologically important hydraulic parameters, including flow depth (maximum and average), average velocity, inundated channel width and wetted perimeter.

The number of hydraulic surveys recommended for the different Reserve levels is prescribed (Birkhead, 1999; Rowlston *et al.*, 2000), with Rapid III, Intermediate and Comprehensive assessments involving a single, two, and four surveys, respectively. Higher accuracy is expected at higher level Reserves, but rainfall variability may determine otherwise. For example, an Intermediate assessment may provide either Comprehensive-type or Rapid III-type (hydraulic) uncertainty if, during the second follow-up survey, the river is flowing either high or low, respectively. Methods for data collection and analysis that are best suited to the different levels of Reserve have been established over the past decade in parallel with the development of South African ecological water assessment methodologies (*viz.* BBM, DRIFT and HFSR), and these are discussed in Sections 9.3.3 and 9.3.4, respectively.

Table 9-2 Data requirements and methods of hydraulic analysis appropriate to different Reserve levels

Reserve level	Data requirements		Methods of analysis	
	Topographic and hydraulic	Habitat hydraulics	Hydraulic	Habitat hydraulics
Comprehensive	Surveys (4) Cross-section(s); and/or 3-Dl bed topography; and water surface profiles; and 1:50 000 scale topographical valley slope. Discharge measurements (4) Velocity-area method; or gauge (including rated section).	Spatial distributions Composition of substrate-types; position of marginal vegetation, depth and depth-averaged velocity.	1-D (uniform or non-uniform), or 2-D	Statistical or spatially explicit depth-averaged velocity distributions.
Intermediate	Surveys (2) Cross-section(s); and water surface profile; and 1:50 000 scale topographical valley slope. Discharge measurements (2) Velocity-area method; or gauge (including rated section).	Spatial distributions Composition of substrate-types; position of marginal vegetation, depth and depth-averaged velocity.	1-D (uniform or non-uniform)	Statistical depth-averaged velocity distributions.
Rapid III	Survey (1) Cross-section; and water surface profile; and 1:50 000 scale topographical valley slope. Discharge measurement (1) Velocity-area method; or gauge (including rated section).	Spatial distributions Composition of substrate-types; position of marginal vegetation, depth and depth-averaged velocity.	1-D uniform	Statistical depth-averaged velocity distributions.

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

Generally, the more hydraulically complex the site (e.g. non-uniform rapidly-varied flow through multi-thread, steep, mixed-substrate channels, as illustrated in Figures 9.3 and 9.4), the greater its hydraulic diversity and ecological suitability for recommending flows, but the greater its reliance on observed data and more sophisticated methods of analysis. Conversely, the hydraulic characterisation of a simpler site (uniform flow within a single-thread alluvial sand channel, as illustrated by the sand run in Figure 9.3) may be achieved using less measured data and simpler hydraulic analyses. For this reason, Rapid III (single survey) assessments for ‘small-scale’ water-use applications are appropriate for sites with low hydraulic complexity. More sophisticated and rigorous hydraulic analyses (i.e. multi-dimensional non-uniform computations) are, however, not necessarily the best use of resources. For Reserve assessments, additional resources for higher levels are allocated mostly for further (hydraulic) field surveys, since this is the surest way of reducing uncertainty. Resource constraints dictate that 2-D hydraulic modeling is undertaken only for selected Comprehensive sites where ecological importance justifies the selection of hydraulically diverse sites and coarser analyses are inappropriate (refer to Table 9.2). Ultimately, the method of hydraulic analysis chosen depends on available resources, resolution of the required output and acceptable level of uncertainty, hydraulic site characteristics, and the range of measured flows.

Reserve applications of hydraulic methods have, to date, not been prescriptive, but rather based on recommendations drawn from experience in providing ecologically relevant information (described by Birkhead,1999; Rowlston *et al.*, 2000; Jordanova *et al.*, 2004). Hirschowitz *et al.* (2007) present an extensive review of hydraulic models and provide recommendations for their use within the Reserve. Stipulating the use of specific methods and models cannot substitute for an understanding of the ecological application and difficulties attendant with modeling conditions of intermediate- and large-scale roughness, as described in Chapter 7. Reserve level and resource constraints are invariably the overriding considerations limiting data collection and the application of hydraulic methods, which are often tailored to suit individual studies and river sites. It is therefore essential to develop an understanding of the Reserve process in general and ecohydraulic application in particular, since these influence the selection of suitable sites and the balance between measured field data and modelled information.

Ecological assessment of the flow requirements of indicator species, guilds or communities requires the characterisation of hydraulic habitat, which may be expressed using variables such as depth and velocity, as well as so-called ‘flow classes’ (described in Sections 9.3.4 and 9.3.5, respectively). A flow class represents a range of values pertaining to at least two environmental variables, of which at least one is flow dependent (e.g. depth, velocity and area of inundation). Flow classes have ecological meaning in that they represent broad preferences of biota for hydraulic and biophysical variables. By employing different methods of hydraulic analysis (statistical at the Rapid III, and spatially explicit descriptions at the Comprehensive), flow class information may be provided for all levels of determination, with different levels of uncertainty.

The interdependence between data collection, methods of analysis, site characteristics and level of Reserve (with associated uncertainty) means that it is difficult to discuss these in isolation. There are however certain requirements, which are discussed in the next sections.

9.3.3 Field information

Selection of field sites

The Department of Water Affairs and Forestry has announced its Water Allocation Reform (WAR) programme (referred to as an important component of the roll-out of the National Water Act of 1998). The main focus of the WAR programme is to reconcile existing and future water demands with availability. Water availability and future planning is addressed using water resource yield modeling that accounts for natural spatial and temporal (time dependent) water distributions, anthropogenic demands on the resource and projected changes in these over time, as well as future operational approaches. It also requires full recognition of the ER, and estimates of EWRs are therefore needed at all points of interest within catchments (termed hydronodes) for water resource planning. The desired future condition of all resources, and therefore the amount of water allocated to their management will be determined through a consultative classification process, according to the guidelines and procedures laid out by the WRCS (Dollar *et al.*, 2006).

The establishment of field sites to assess EWRs for all hydronodes, which is necessary for nationwide water resource planning, is not pragmatic or practical in the light of available resources. The location of sites is therefore based on the longitudinal division of rivers into Resource Units (RUs) that are sufficiently different to warrant their own specification of the Reserve. Resource Units have clearly defined geographical boundaries (Louw *et al.*, 1999), are delineated primarily on a biophysical basis, and are called Natural RUs. Management requirements must also be considered (e.g. the location of a large dam and/or transfer scheme), and in these instances, the RUs are termed Management RUs (MRUs) (Kleynhans and Louw, 2007). The following are considered in the selection of MRUs: Ecoregion classification (Level II); geomorphic zones; land cover; dams and other operational aspects; water quality; groundwater; and local knowledge. In ecoregional classification (developed in the USA by Omernik, 1987), rivers are grouped on the basis of similarities in certain attributes. Level I classification (Kleynhans *et al.*, 2005) applies the following attributes at a broad scale: physiography, climate, rainfall, geology and natural vegetation cover. Level II (Kleynhans *et al.*, 2007b) uses the same attributes but in more detail. Rowntree and Wadeson (1999) developed a geomorphological zonal classification system for southern African rivers, modified from Noble and Hemens (1978). River zones are assigned a geomorphological definition based on distinctive channel units (termed geomorphological, geomorphic or morphological units) and reach types. Studies on different South African rivers also revealed that longitudinal channel gradient was a further indicator of channel characteristics.

Field sites are selected within MRUs, but since it is not always possible to include all units or hydronodes requiring EWRs for water resource planning, principles of extrapolation and/or estimation are required (Section 9.3.6; Birkhead and Kleynhans, 2008). The selection of EWR sites is guided by the following key considerations (Louw and Kemper, 2000): accessibility, diversity of physical habitat for aquatic and riparian biota, suitability of sites for hydraulic modeling over a range of flows, especially low flows, and river sections that are ‘critical’ for ecosystem functioning. Critical sections are usually characterised by an increase in local channel gradient, forming so-called ‘rapids’ and ‘riffles’ (Figure 9.3), where low-flow conditions or the cessation of flow would constitute a break in the ecological functioning of the river (i.e. these sections usually dry up). Flow-sensitive (rheophilic) biota that depend on these hydraulic conditions, and/or perennial flow, would be adversely affected by a loss of flow and/or surface water. This is the rationale for directing attention to these morphological units when selecting sites in perennial systems with flow-sensitive biota.

Box 9.2

Morphological units and biotopes

Hydraulic analyses for Reserve assessments are typically associated with 'rapids', 'riffles', 'runs' and 'pools'.

> *In rapids, flow is fast and turbulent with an intermittent white water surface and breaking waves (i.e. hydraulic jumps); riffles are associated with small ripples, waves and eddies, and are generally shallow compared with average river depth; the surface flow in runs is relatively smooth with an unbroken surface; and pools are characterised by low (or no) velocity, a smooth water surface and are usually deep compared with average river depth* (Figure 9.3) (adapted from Peck *et al*., 2001).

These features, defined here using surface flow characteristics (refer to Chapter 4), are basic units of channel morphology as well as so-called 'biotopes'.

Two major bodies of work on river classification (*viz*. van Niekerk *et al*., 1995 and Rowntree and Wadeson, 1997) have emerged from the South African literature since the early 1990s, borne out of the requirements of ecologists for a physical description for aquatic ecosystem management (Dollar and Rowntree, 2003). Dollar and Rowntree (2003) show that both these two hierarchical classifications define 'morphological units' according to the same spatial scale (order of channel width), and describe these as '*the basic erosional or depositional features comprising the channel morphology*'.

'Biotopes' describe the abiotic environment (generally the depth, velocity and substrate) of a community of organisms (Wadeson and Rowntree, 1998), but is sometimes used in reference to only the hydraulic/substrate conditions (i.e. 'hydraulic biotopes'). The differences between morphological units and hydraulic biotopes are discussed further in Chapter 4. In this chapter, these features (i.e. rapids, riffles, runs and pools) are collectively described as 'morphological units'.

It does not follow that morphological units with slower flow (e.g. runs and pools) are unimportant or disregarded in ecological flow assessments. These units usually do not provide critical hydraulic conditions in these hydro-ecological systems (i.e. perennial systems with flow-sensitive biota). Critical hydraulic conditions therefore occur in morphological units associated with the highest flow requirements. Pools, however, provide hydraulic habitat for less flow-sensitive biota, and need to be considered if semi-rheophilic or limnophilic guilds or communities are used as indicators of flow requirements. These taxa are able to function, or at least maintain life, during periods of extremely low or no flow, although the suitability of hydraulic habitat may be compromised through reduced vegetation cover for fish and water level drawdown along the channel margins (as well as water chemistry and temperature considerations). Pools may also be important when assessing sediment transport characteristics of modified flow regimes (Dollar and Rowntree, 2003), since these units are more susceptible to sedimentation than higher gradient (energy) units. Finally, Reserve level is also a key consideration influencing site selection and suitability from a hydraulics perspective, as illustrated in Figure 9.2.

Figure 9-3 Typical cobble/boulder rapid (top left), cobble/gravel riffle (top right), sand run (bottom left) and pool (bottom right) features representing critical and/or important morphological units used for ecological flow assessment (*Photographs D Louw*).

Since the purpose of the ER is to determine the flow regime that will maintain the river in a certain ecological state or category, biotic considerations tend to dominate site selection. Sites providing indicators of biotic response to flow variation commonly display a high degree of physical and hydraulic diversity, which is complex to characterise, especially at low flows. While hydraulic considerations cannot benefit from pre-eminence in site selection, it is important that they influence the process to the extent that sites chosen are not of such hydraulic complexity that reliable analysis and prediction is impractical. This is even more the case when hydraulic data are limited (i.e. for lower assessment levels). A site that is difficult to characterise hydraulically is likely to produce information of high uncertainty, with consequent implications for the EWR. An example of such a site is one characterised by distributary channels, which, due to different hydraulic controls, invariably flow at different stages and have large variations in average velocity between channels. Figure 9.4 illustrates one such distributary channel in the mixed-anastomosing channel-type illustrated in Figure 9.5.

Figure 9-4 Distributary channels in a multi-thread mixed-anastomosing channel-type along the Sabie River (Figure 9.5) (*Photograph D Louw*)

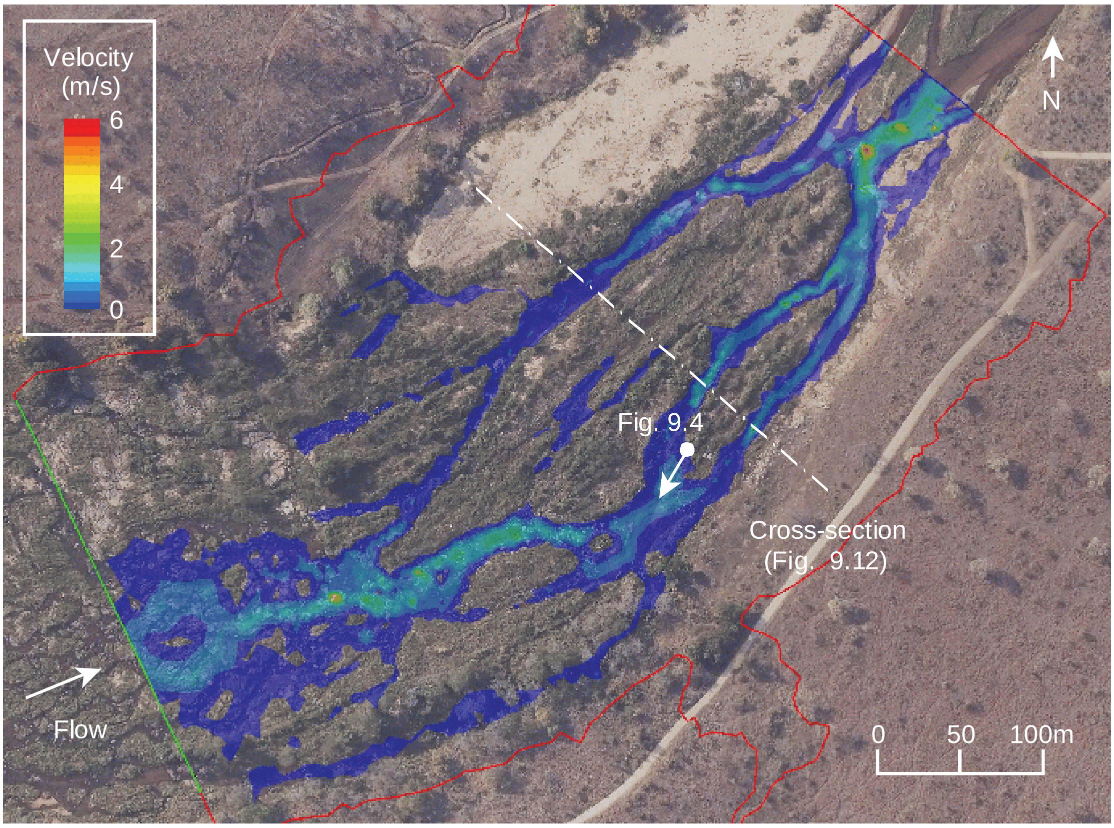


Figure 9-5 Aerial photograph of a Reserve site (mixed-anastomosing channel-type) along the Sabie River (Kruger National Park, South Africa: 24°59'12''S 31°17'34''E). The modelled area (River2D) is indicated in red with the upstream boundary in green. The inundated region for a discharge of 7.8 m^3/s is rendered using the 'hot-cold' shading representing velocity magnitude.

Locating sites can be difficult, frustrating and time-consuming, and selection is greatly assisted by the use of aerial video surveys tracked through synchronised time to a Global Positioning System (GPS). For larger river and floodplain systems, the use and accessibility of Google^{TM} Earth satellite images are invaluable for viewing high-resolution photographs, where available. For example, high-resolution satellite images facilitated an assessment of the minimum number and location of cross-sections (from both hydraulics and biophysical perspectives) for an 11 km zone of the Mokolo River floodplain system (South Africa), as illustrated in Figure 9.6. Floodplain inundation was modelled using the HEC-River Analysis System, described in Section 9.3.4.

Site selection is preferably undertaken during low flow (but not no-flow) periods, when bed features (hydraulic controls) are not inundated, and flow-sensitive areas such as riffles can be located. This is essential for Rapid III assessments that involve only one field survey at a low flow. Experience has shown that sites selected during high flows (due to, for example, untimely rainfall or unfavourable study scheduling) are often unfavourable for low flow determination, in that they are not particularly flow sensitive (i.e. runs or pools) or hydraulically complex. Site selection during high flows should therefore be avoided.

As discussed previously (Section 9.3.2 and Figure 9.1) the degree of hydraulic complexity that can reasonably be dealt with in an ER assessment depends primarily on the Reserve level and characteristics of accessible sites in the RU. Invariably, there is a compromise between hydraulic and ecological site suitability, since high ecological suitability usually implies high hydraulic complexity. Therefore, to ensure that hydraulic uncertainty is appropriate for the Reserve level, hydraulic criteria prevail at lower level assessments (i.e. Rapid III). This is due to the reduced amount of measured data and approximations in coarser hydraulic analyses (discussed in Section 9.3.4).

For all levels of assessment, the following hydraulic characteristics (which are seldom found in natural river systems) are favoured, in the following approximate order of decreasing importance:

- Equivalent (i.e. horizontal) cross-channel stages
- Similar average velocities in cross-river channels
- Natural hydraulic controls due to local resistance
- Approximately uniform flow (equal longitudinal water surface and channel bed gradients)
- Zero depth at the cessation of flow (i.e. flow sensitive site)
- Single river channel
- Low and uniform flow resistance (small-scale bed and bank roughness elements)

Safety issues associated with the natural inhabitants of rivers (hippopotami, crocodiles and the risk of contracting water borne diseases such as bilharzia and giardia) as well as the entry into flooding rivers, have been discussed elsewhere (Rowlston *et al.*, 2000). In addition to these risks, there is ever increasing concern for field safety in southern Africa due to criminal activities, and it is advisable to take steps to ensure safety from these threats.

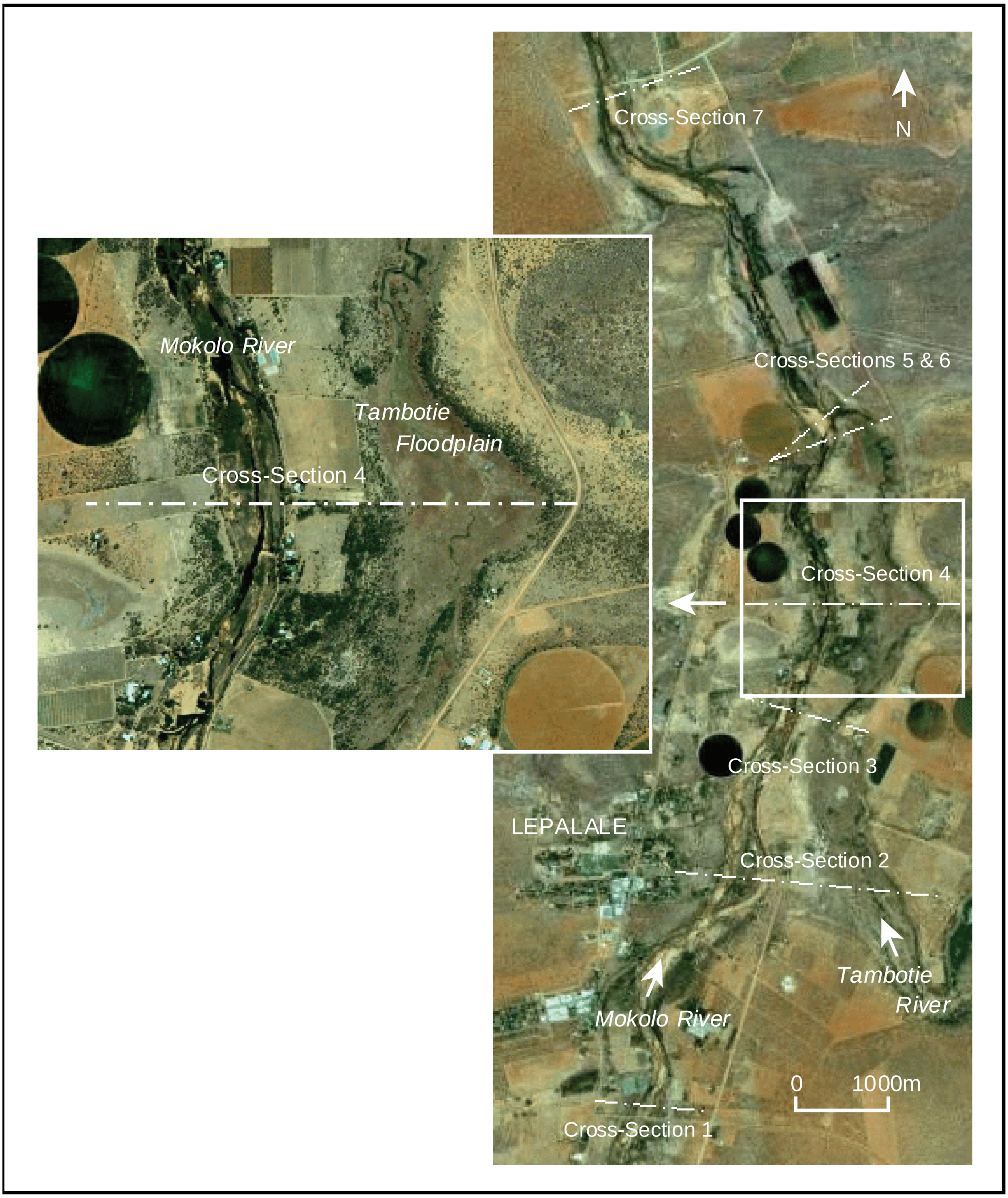


Figure 9-6 Google™ Earth satellite images of an 11 km zone of the Mokolo River floodplain system at Lepalale (Limpopo Province, South Africa: 23°47'38''S 27°46'00''E), showing the positioning of cross-sections based on hydraulic and biophysical criteria. The arrows indicate flow directions, and the floodplain view at Cross-section 4 shows the high resolution imagery.

Topographical surveys

Topographical surveys are necessary to define the river channel in sufficient detail to enable hydraulic modeling at a resolution suitable for ecological interpretation. Depending on the Reserve level and site complexity, topographical surveys may include the following (refer to Table 9.2).

- Single cross-sectional survey (i.e. 2-D)
- Multiple cross-sectional surveys (spatially independent or linked)
- 3-D survey of a river site

Resource and time constraints dictate that lower-level assessments include a survey of a single cross-section, generally positioned through hydraulic conditions sensitive to changes in low flows (i.e. a riffle or rapid). For Intermediate and Comprehensive levels, multiple cross-sections may be required for both hydraulic modeling purposes and to provide hydraulic information suitable for biophysical (geomorphological and ecological) flow assessments. Hydraulically, multiple cross-sections are required for non-uniform analyses (discussed in Section 9.3.4), and these cross-sections are positioned so as to characterise natural and artificial controls that influence stage-discharge relationships at sections of interest (i.e. those used for flow assessment purposes). More than one cross-section may also be required to provide suitable hydraulic information for different components of a holistic assessment. For example, whereas riffles and rapids provide critical hydraulic conditions for rheophilic fauna, pools are susceptible to sedimentation and may be important from a geomorphological perspective.

There is good reason for using single rather than multiple cross-sectional surveys for all levels of assessment where the above suitability requirements (hydraulic and biophysical) are met. As discussed in Section 9.3.2, additional resources for higher level assessments are usually allocated to further field surveys as the best means of reducing hydraulic uncertainty. Non-uniform (use of multiple cross-sections) and 2-D hydraulic analyses require additional topographical and hydraulic data (for model development and calibration) as well as boundary rating functions (which generally assume uniform flow conditions anyway!). Furthermore, they do not avoid the need to estimate of the most difficult-to-determine parameter: flow resistance. For these reasons and if site conditions allow, resources are rather allocated to data collection with the use of single cross-sections for describing critical hydraulic conditions. Suitable cross-section positioning is essential to characterise critical hydraulic habitat for the biota being considered. For example, when considering the flow requirements of flow-sensitive fish guilds and invertebrate communities, fast flow (> 0.3 m/s) over coarse substrate (with cover for fish) is the critical hydraulic habitat. A recent study (Birkhead, 2008) indicates that trading-off a degree of hydraulic accuracy to ensure that cross-sectional positioning adequately describes critical conditions, may be justified. Experience with ecological flow assessments using South African methodologies (described in Section 9.2.3) has shown that incorrect cross-sectional positioning, with reference to critical hydraulic habitats required for flow-sensitive biota, generally results in over-estimation of the flow requirements. Changes in flow direction with discharge also need consideration when locating cross-sections.

Three-dimensional Digital Terrain Models (DTMs) (discussed in Section 9.3.4) are required for 2-D hydraulic modeling. These may be developed through spatial interpolation of conventional land-based surveys of cross-sections (Jordanova *et al.*, 2004; Hirschowitz *et al.*, 2007), or point surveys of significant changes in slope covering the region of interest (Jordanova *et al.*, 2004), or by airborne laser mapping (Birkhead *et al.*, 2007). Point surveys produce more accurate DTMs than spatial cross-sectional interpolation, but are more time consuming. A combination of these may be used, with point surveys in areas that benefit from a more accurate description of the low-flow bed topography.

River surveys extend from bank to bank of the macro-channel, and incorporate all significant changes in slope. Roughness elements that are frequently (i.e. annually) transported constitute the overall channel bed resistance, and are not surveyed in minute detail. Larger sedimentary deposits that are infrequently moved are included in the survey, since these features reduce flow area for all but the highest floods. Surveys of the thalweg (lowest bed elevation in a longitudinal direction) are useful, as they allow stages or depths at the cessation of flow to be determined (refer to Equation 9.1). This also enables the relative elevation of interpolated cross-sections to be adjusted (in elevation) for non-uniform computations (e.g. using HEC-RAS as described in Section 9.3.4). If the river is flowing strongly during the site selection, the actual positioning of cross-sections may be postponed to follow-up surveys. Under such circumstances, stage data are collected along the river banks and reconciled with the positioning of cross-sections during a later topographical survey.

The equipment best suited to undertaking most river surveys for Reserves is a Total Station with onboard data recording. For rivers with extensive floodplains and wetlands, differential GPS (as used to survey the cross-sections indicated in Figure 9.6), that has greater mobility, and airborne laser mapping are the preferred methods.

Laser mapping has become a well established technology in the field of remote sensing. It 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. Since water surfaces usually have little reflectance, terrestrial laser mapping does not penetrate water. Terrestrial Light Detection and Ranging (LIDAR) was successfully used to survey the Nylsvley Wetland (Birkhead *et al.*, 2007), and a Reserve site along the Sabie River (Figure 9.5), but required the water surface to be artificially lowered to ‘generate’ the river channels which were inundated at the time of the aerial survey. Water-penetrating LIDAR has been used for hydrographic surveys since the late 1980s. System costs (approximately US$ 3m) and the fact that it only penetrates three times further than the human eye (a limitation in many sediment-laden South African rivers) mean that LIDAR surveys for accurate river channel mapping should be carried out with no surface water. The cost of terrestrial LIDAR surveys limit their general use in Reserve assessments for rivers, but may be warranted for mapping extensive wetland and floodplain systems.

Permanent linked stations (or benchmarks) are placed at sites for future surveys, and are surveyed relative to each other to an acceptable accuracy (±10 mm), particularly for sites characterised by mild water surface gradients. Benchmarks provide the survey datum, in elevation and plan, and can be local or relative to the National LO coordinate system. The latter is useful, since it allows datums to be re-instated if fixed stations are removed through vandalisation and/or flooding.

Flow variables

An updated discussion of the measurement of flow variables as presented by Birkhead (1999) and Rowlston *et al.* (2000) follows:

To be of use in holistic ecological flow assessments, flow-related variables such as depth, velocity and wetted perimeter must be related to discharge. Various methods exist for measuring discharge, including the use of rated sites (natural river sections or structural gauges) and manual techniques such as the velocity-area method. In South Africa, rated sites fall under the auspices of the DWAF, and rating tables, data quality codes and hydrological observations (instantaneous, daily and monthly) are available on the DWAF hydrological website at the following address: http://www.dwaf.gov.za/hydrology. Flow for selected gauges are also available on the internet at near real time, which greatly assists with the scheduling of field trips to measure hydraulic conditions under as wide a range of flows as possible. Photographs of selected gauges are also available on the website. A gauging weir or rated cross-section located in close proximity to a Reserve site provides a useful means of obtaining discharge data. The integrity of data must not be taken for granted, however, and it is advisable to manually read gauge plates during field trips and to check the quality of data with the authority responsible for its operation. Gauges must be sufficiently close to sites that intervening inflows and losses can either be ignored or accounted for by measurement. Furthermore, care should be exercised when field trips are undertaken during unsteady flow conditions, i.e. when flow is increasing or decreasing, to account for the travel time and attenuation of discharge between the gauge and flow assessment site. A method for synthesising rating relationships based on the measurement of a stage and discharge hydrographs at a local site and remote gauge, respectively, is provided by Birkhead and James (1998).

The velocity-area method is undoubtedly the most commonly used manual technique for determining discharge in ungauged rivers in South Africa. Although dilution techniques may be better suited to small rivers with a high degree of mixing (turbulence) where it is difficult to measure point velocities, they have yet to be applied in South Africa for routine discharge determination. For the correct application of discharge measurement techniques, details and standards for the application of manual gauging methods are given in the Standards for the Measurement of Liquid Flow in Open Channels (British Standards (BS) 3680, 1980 and 1983). Gordon *et al.* (1992) also give easily understood descriptions. It is desirable to include measurements during floods in Comprehensive level assessments to obtain as wide a range of discharges as possible. Where depth and velocity may militate against safely entering the water (including the use of boats), surface velocities and stage may be measured at the sites or from a local bridge deck, with post-flood cross-sectional surveys providing the flow area.

In Reserves, measured data are limited (e.g. one rating point for a Rapid III assessment), and therefore accuracy is important. The error in discharge measured in the field influences consequent analyses, and should therefore be measured to a high level of accuracy. This is strongly influenced by the selection of a suitable cross-section for manual velocity-area gauging. Discharge through a cross-section with large roughness elements (e.g. a rapid or riffle) and in pools with low velocities (less than approximately 0.05 m/s) are difficult to measure accurately. Suitable cross-sections for manual gauging are prismatic, have materially uniform flow (i.e. flow conditions do not change along the length of the river) and have water considerably deeper than the height of the resistance elements constituting the bed. These conditions seldom occur at Reserve sites (which are selected based on other criteria), and flow gauging may be preferable at cross-sections remote from the site, but sufficiently close to ignore inflows or losses.

Box 9.3

Riparian zones and marginal vegetation

Riparian zones are plant communities contiguous to and affected by surface and subsurface hydrological features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, and drainage ways). Riparian zones have one or both of the following characteristics: distinctly different vegetative species than adjacent areas, and species similar to adjacent areas but exhibiting more vigorous or robust growth forms. Riparian areas are usually transitional between wetland and upland (FISRWG, 1998).

Marginal vegetation is the narrow band of vegetation within the riparian zone directly adjacent to surface water at base flows.

Rating relationships, as described in Section 9.3.4 and Chapter 7, are fundamental to hydraulic analyses, and therefore, at each site visit when discharge is determined, stages are surveyed relative to the fixed stations. Water levels are surveyed at active channel banks for cross-sections and along banks for 3-D DTMs. In addition, stages are measured upstream and downstream of the cross-section/s or DTMs to provide water surface slopes. These are necessary for estimating high-flow energy gradients required for synthesising additional rating points, as described in Section 9.3.4.

Other biophysical data

As discussed previously, the purpose of ecohydraulics in the ER is to provide information suitable for assessing ecological flows, both in terms of drivers (i.e. flow, morphology and water chemistry) and biological responses (Figure 9.1). Therefore, in addition to information required for hydraulic analyses, as discussed in the previous two sections, site-specific biophysical information is necessary. This includes the relative position of topographical features for assessing flows of morphological interest (e.g. location of benches) and for biotic requirements (generally used for assessing the requirements of riparian vegetation – refer to Figure 9.12). These features are surveyed across the river cross-section/s (when undertaking a uniform flow analysis) or within the modelled region (for 1-D or 2-D non-uniform flow analyses).

The use of depositional morphological features for assessing flow requirements is of limited value in southern Africa for two main reasons. Firstly, most rivers are influenced by the occurrence of bedrock influence and relatively few are completely alluvial (i.e. flowing within their transported sediment) and therefore have very little morphological capacity to adjust to long-term flow patterns. Secondly, rainfall and flow are highly variable, resulting in a high relative difference between infrequent flow events and annual or two-year return interval floods. The typical ‘bankful-type’ morphologies, which are characteristic of temperate climates, therefore do not develop. Often, depositional features can result from single large infrequent events, and not in response to more regular floods (i.e. with annual or two-year return intervals). Furthermore, alluvial sites are seldom selected for ecological flow assessment, since they rarely represent areas of critical instream ecosystem functioning within the RU. Sediment transport analyses are increasingly used for addressing geomorphological flow requirements (Dollar and Rowntree, 2003). These approaches, which are reliant on basic hydraulic information, seek to maintain the potential for transporting bed material (i.e. avoiding excessive sediment deposition), and are therefore more appropriate for application to flow-reduced southern African river systems. Such methods are discussed in Chapter 8.

As may be noted from Table 9.2, certain information is required for describing habitat hydraulics (refer to Section 9.3.5), including the following.

- Size-composition and spatial distribution of substrate
- Position and average height of marginal vegetation
- Point measurements of depth and depth-averaged velocity within the critical morphological feature/s of interest (e.g. rapid, riffle or run)

The South African Scoring System (SASS), a method developed by Chutter (1998), and in standard use in South Africa to broadly assess water quality on the basis of presence and sensitivity of aquatic invertebrate families, is based on sampling of various sediment types and marginal vegetation. Well-known biotope classifications (refer to Text Box 9.2 and Chapter 4 for a description of biotopes) used in the SASS are 'stones in-current' and 'stones out-of-current'. From an ecohydraulics point of view, these descriptions are not very useful, since the results of hydraulic analysis are usually expressed numerically. Numerical information can be represented by descriptive categories, but not *vice versa*. It is therefore necessary to express qualitative classifications (e.g. 'stones-in-current' or 'surface flow types' – the latter are described in Chapter 4) using numerical parameter values.

Preliminary numerical ranges for substrate size (diameter) and depth-averaged velocity used to define invertebrate flow classes are given by Jordanova *et al*. (2004). Two broad substrate categories are used: fine sediment (dia. < 16 mm) and coarse sediment (dia. > 16 mm). A particle diameter of 16 mm separates medium and coarse gravels according to the Rowntree (2000) classification. Bedrock is defined as a third substrate class. These three classes have been modified in subsequent flow assessments, with coarse sediments ranging in diameter from 16 mm to 250 mm (i.e. up to boulders). Larger boulders have been grouped with bedrock, since these are similar substrate types in terms of suitability as invertebrate habitat. It is recognised that large gravels and loose cobbles (i.e. coarse sediments) are more suitable substrate than finer sediments which are frequently transported, and boulders which are less frequently mobile and therefore more easily embedded with a loss of interstitial spaces. The number of substrate classes (i.e. three, including fine sediments (0-16 mm), coarse sediments (16-250 mm), boulders (>250 mm) and bedrock), has been kept to a 'meaningful' minimum, since each is, in turn, associated with a range of velocity classes, resulting in a larger number of flow classes.

Box 9.4

Embedded sediments and interstitial spaces

Embedded sediments refer to the substrate condition where the interstitial spaces between coarse sediments, such as cobbles, are filled with finer particles (gravel, sand and silt). Interstitial sediments reduce the suitability of substrate habitat for aquatic organisms, and the removal of fine sediments for channel maintenance is discussed in Chapter 8.

Another habitable surface used by certain invertebrates is inundated vegetation. The position of suitable marginal vegetation is surveyed relative to the channel topography for predicting the extent of inundated vegetation at different stages. Although 1-D hydraulic analysis is commonly used, substrate composition and the presence of suitable marginal vegetation are surveyed at the morphological unit scale, but represented using a 2-D cross-section.

Substrate characteristics and inundated vegetation also contribute to an essential feature of fish habitat, called ‘cover’. Cover is defined as any structure or vegetation which influences activities and/or concealment (Hardy *et al.*, 2006), and therefore includes such features as undercut banks, root wads and overhanging vegetation. Presently, cover is not explicitly included in the biophysical data collection used for deriving flow class information. The abundance and suitability of cover is assessed, however, as part of site-specific ecological data, and is used when interpreting flow class information.

A photographic record of the site at known discharges is used extensively in ecological flow assessments, and photographs are taken from a subsequently identifiable and repeatable position whenever site visits are undertaken (Louw and Kemper, 2000; Rowlston *et al.*, 2000). Photographs are taken of the cross-section/s (for 1-D modeling as well as 2-D modeling where the DTM is developed using multiple cross-sections) as well as flow-sensitive areas (e.g. shallow flow over coarse sediments and marginal vegetation) that are useful for qualitative assessments of changes with discharge (for further details refer to Louw and Kemper, 2000). It is essential that photographs correspond to known discharges, preferably measured at the time of exposure, or by surveying stage and using rating information from the hydraulic analysis.

An extensive photographic record and corresponding hydraulic information were collated by Desai (2007) using previous IFR and ER studies undertaken in southern Africa. Ninety-two sites from thirteen studies are included in a MS-Access data-base that can be searched according to flow resistance, depth, morphological unit type (e.g. rapid, riffle and pool) and substrate type. The database provides a photographic matching guide for estimating flow resistance for use in hydraulic modeling, and is available electronically from the Water Research Commission (South Africa) appended to the report of Hirschowitz *et al.* (2007).

9.3.4 Hydraulic modeling

Hydraulic modeling is necessary to provide ecologically relevant information over a range of discharges. This cannot be achieved by periodic on-site hydraulic measurements alone. Hydraulic models used in South African ecological flow assessments, but equally relevant to ecohydraulic studies, include the following:

- 1-D and 2-D models for non-uniform unsteady flow analysis. The numerical dimensions refer to the directions of motion (i.e. longitudinally (1-D) and longitudinally/laterally (2-D)), and not to temporal effects (i.e. unsteady flow).
- Lateral distribution models for predicting the cross-channel distribution of depth-averaged velocity based on cross-sectional and hydraulic information.
- Models based primarily on field measurements (i.e. largely empirical). These include models for predicting frequency-distributions of depth-averaged velocity and ecohydraulic methods used for desktop Reserve assessment (refer to Section 9.3.6).

A large number of computational models are available for open-channel hydraulics, with various 1-D and 2-D models reviewed by Hirschowitz *et al.* (2007). Two of these were further investigated for use in ERs: HEC-RAS (1-D), which has been applied to river and wetland ecohydraulic studies (Birkhead *et al.*, 2007; Kleynhans *et al.*, 2007a), and River2D. In South Africa, the accessibility of models is important, due to limited resources and the high cost of commercial products. For this reason, the recommended computational software is freeware and is available on the internet for download.

Different means of providing hydraulic information for Reserve assessments are illustrated in the flow chart in Figure 9.7, and the model types are described in the following sections (note that the flow chart is not intended for assessing an appropriate modeling approach).

Rating relationships

A fundamental requirement in ecohydraulic studies is the prediction of the relationship between stage and discharge, or rating. A rating applies to any point in a river channel, and stage, i.e. the water surface elevation relative to a datum (e.g. above mean sea level as illustrated in Figure 9.8) can be expressed as depth, i.e. the water surface elevation relative to the bed. Where the cross-river water surface elevation is horizontal, a rating applies to the section, with the depth being the maximum across the section. One-dimensional hydraulic analyses account for motion in the longitudinal (upstream/downstream) direction only, and horizontal cross-river water surfaces therefore apply. Ratings are the coarsest level description in ecological flow assessments requiring hydraulic information (i.e. Rapid level III and higher).

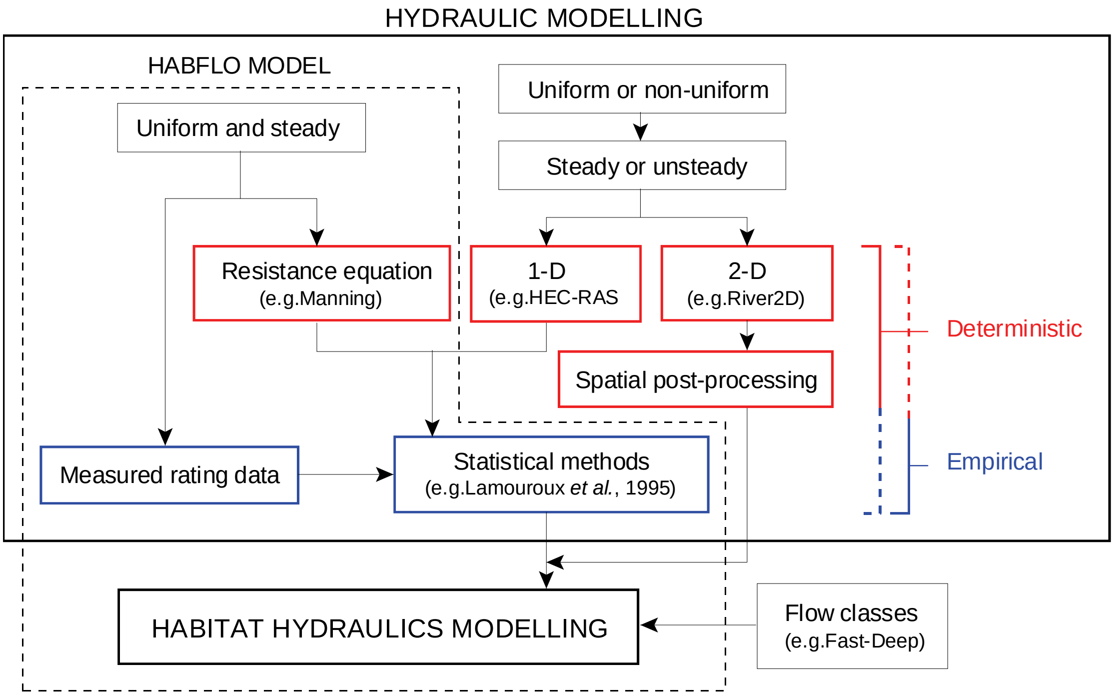


Figure 9-7 **Flow chart showing the model types used in ER assessments (refer to Table 9.2 for corresponding Reserve levels). The 'largely' deterministic methods (*viz.* resistance equations, 1-D and 2-D modeling) are differentiated from the 'largely' empirical approaches (*viz.* measured rating data and statistical methods).**

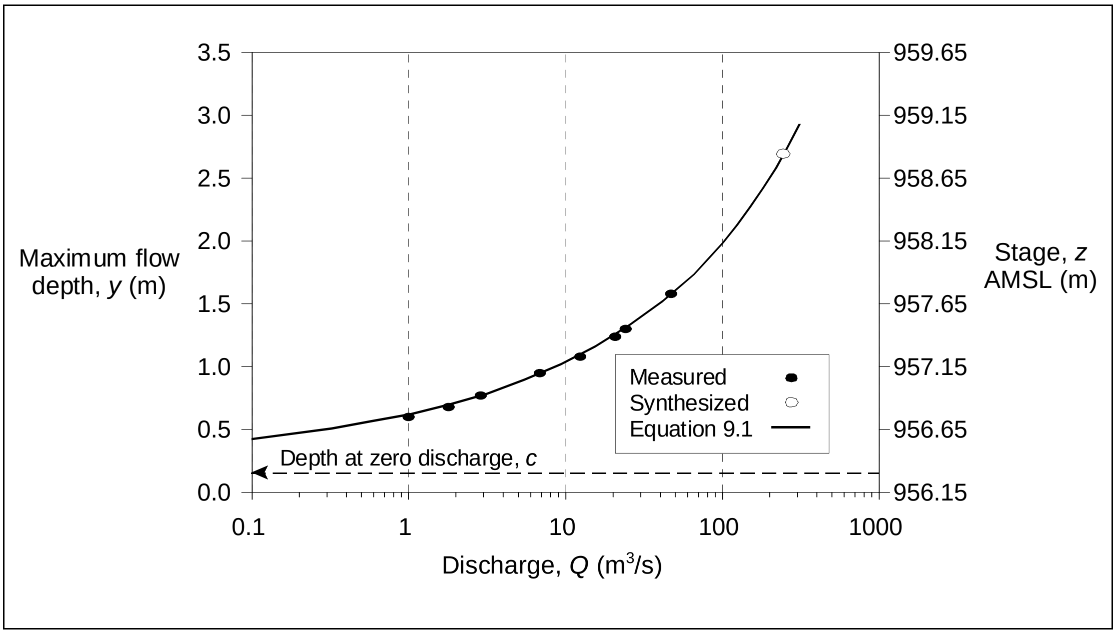


Figure 9-8 **Example of a rating curve developed using measured and synthesised data points and plotted on log-normal axes. Discharge is plotted against maximum depth as well as stage (AMSL = Above Mean Sea Level).**

In ER studies, modeling of rating relationships involves interpolation between measured data points and extrapolation beyond the limits of observed data. An exception is for Rapid III assessments, where a single rating point is surveyed, and the relationship is therefore entirely extrapolated. The power relationship given by Birkhead and James (1998) has been widely used in Reserve and broader ecohydraulic studies to express ratings as simple continuous functions, given by

$$y = aQ^{b} + c \tag{9.1}$$

where y is the flow depth (m), Q is the discharge (m^3/s), and a, b and c are coefficients generally determined by regression. The constant c has hydraulic meaning: physically, it represents the depth at zero discharge, or the 'pooled' water remaining in the river due to downstream structural controls, when flow ceases.

Equation 9.1 is monotonic, implying that the coefficients are constants and do not depend on temporal conditions, e.g. unsteady flow and seasonal changes in vegetation resistance. This is appropriate, since steady-state hydraulic analyses are suitable for Reserve sites along rivers. For large wetland and floodplain systems, unsteady analyses may be required to account for changes in reach storage (Birkhead *et al.*, 2007). In addition to channel storage, reach storage may include sub-surface water in banks, and a method for synthesising approximate steady-state rating curves using hydrological routing is described by Birkhead and James (1998, extended in 2002 to include bank storage).

The measurement of rating data was discussed in Section 9.3.3. When sufficient field data exist an empirical rating function may be developed based entirely on field observations. Although this is desirable, in terms of accuracy, it is seldom the case in Reserve studies, even at the Comprehensive level. Generally, extrapolation beyond the limits of measured rating data is necessary.

As discussed in Section 9.3.2, hydraulic data collection places precedence on low flows. This is because Reserve sites typically characterised by large substrate elements (i.e. rough beds) which result in high flow-resistance that depends on relative flow depth (Chapter 7; Jordanova and James (2007)). Synthesis of rating data requires an estimate of flow resistance, and accurate estimation of low-flow resistance for rough beds is difficult – hence the prioritisation of low-flow data collection. Also discussed previously is the selection of field sites that are typically sensitive to changes in flow. A consequence of this is that depth is zero at the cessation of flow (i.e. $c = 0$ in equation (9.1)). Indeed, (critical) cross-sectional positioning aims to produce this result, particularly for lower level assessments (e.g. Rapid level III) where hydraulic data are limited and single cross-sections are invariably used. This implies an additional 'measured' rating point at $(y;Q) = (0;0)$. For these cross-sections, a continuous rating relationship (e.g. equation (9.1)) may be fitted to measured data augmented by a synthesised rating point at a suitably high discharge. This discharge value should correspond to a depth where the relative contribution of bed resistance is judged to be low – i.e. flow resistance ought to be estimated with higher certainty than at low flows.

In addition to morphological units with a local increase in channel gradient (e.g. rapids and riffles), lower gradient units such as runs and pools may also require hydraulic characterisation for the various reasons discussed in Section 9.3.3. At the cessation of flow, there is usually a residual depth remaining in these units, particularly for pools (by definition). For cross-sections through these units, the residual flow depth (i.e. 'c' in Equation 9.1) may be determined, in order of preference, by

- measuring the residual depth at the cessation of flow or at an extremely low discharge, or
- surveying the longitudinal bed slope at the lowest cross-channel elevation for a sufficient distance downstream (i.e. along the 'thalweg') to determine the hydraulic control causing backup, or
- non-linear regression, i.e. fitting Equation 9.1 to rating data.

At certain sites, the continuous form of Equation 9.1 does not satisfactorily describe the variation in the rating data, and two intersecting curves are necessary to obtain a reasonable fit. Once a rating relationship has been developed, relationships between discharge and other ecologically useful hydraulic determinants – most importantly average depth, average velocity, inundated width and wetted perimeter – are easily computed using results of the topographical surveys, previously described in Section 9.3.3. These relations may be for individual cross-sections or average values for selected river reaches.

One-dimensional analyses

One-dimensional hydraulic analyses consider flow in the longitudinal direction only (i.e. in the downstream direction), and motion in lateral (cross-channel) and vertical directions are neglected. Topographical cross-channel characteristics are accounted for using cross-sectional information derived from topographical surveys and the specification of the lateral variance in flow resistance, levees, ineffective flow areas and obstructions (refer to 'non-uniform flow profiles' in the section below). One-dimensional analyses are therefore appropriate where flow is principally in a longitudinal direction, and this is the case in many rivers reaches, particularly where high flows are concerned (topographical controls inducing lateral flow become drowned-out). As discussed previously, diversity of hydraulic conditions and hence the suitability for assessing ecological flows increases with physical complexity, which, in turn, is associated with multi-dimensional flow patterns. It is therefore necessary, mainly through inter-disciplinary experience, to develop an ability to assess the value (to the ecological flow assessment) and necessity of employing more sophisticated and rigorous methods of analysis (*viz.* 2-D or even 3-D). In South Africa, resource constraints dictate that sites are favoured where 1-D uniform flow analyses are suitable. For more hydraulically complex sites, there is a penchant for additional field data rather than more rigorous hydraulic modeling, with additional data coupled to higher level Reserves. Therefore, Rapid III assessments (minimal field data) are intended for use at sites with relatively simple hydraulic characteristics (*viz.* horizontal cross-river stage in a single channel, low and uniform flow resistance, uniform flow conditions and a site that dries-up at the cessation of flow), but nonetheless useful for flow assessment.

Uniform flow conditions

True uniform flow conditions seldom, if ever, occur in natural water courses – particularly at sites suitable for ecological flow assessment. This is because channel shape and slope vary with distance downstream, since sediments are mobile and flows vary temporally and spatially. Sites are favoured where flow conditions are approximately uniform, observed by a roughly constant water surface slope, and average cross-channel depth and velocity over the length of the morphological unit of interest. Generally, the local water surface slope provides a better approximation of the energy gradient than the local bed slope, since changes in cross-sectional shape, bed slope and flow resistance influence the energy gradient (through changes in depth and velocity). It is also difficult to define the 'bed level' for beds with large substrates.

A uniform flow approximation implies the use of a single cross-section, located within the morphological unit of interest, and supporting, as far as possible, the hydraulic requirements mentioned above. The use of cross-sections to derive hydraulic information used in flow assessments for RUs, is important, and warrants re-emphasis:

Taking account of the characteristics of the hydro-ecological system (e.g. perennial river with flow-sensitive biota), a cross-section is surveyed across the morphological unit associated with critical or important hydraulic conditions (e.g. a riffle). The cross-section represents hydraulic conditions within the unit, which, in turn, represents critical hydraulic conditions at the site and within the RU. A site is not selected to be representative of the RU, and similarly, a cross-section is not selected to be representative of the site. An appreciation of the use of hydraulic and biophysical information from these different spatial scales (i.e. cross-section, morphological unit, site and RU) is important for understanding the approach for modeling habitat-hydraulics, described in Section 9.3.5.

For uniform flow, resistance equations may be used to synthesise rating data to supplement measured data. Well known resistance equations (e.g. Manning, Cheźy and Darcy-Weisbach) and the relationships between coefficients are described in Chapter 7. According to Rowlston *et al.* (2000), the selection of a suitable resistance equation is arbitrary and should be based on pragmatic considerations, such as, for example, the resistance formulation applied in the software used, experience and familiarity. Their justification is based on the recognition that although some relationships are theoretically more rigorous than others, it is illogical (and misleading) to apply the most rigorous modeling approach in a situation where the resistance coefficient is essentially a ‘composite’ calibration factor based on field data. This factor and the energy losses cannot be derived solely from consideration of the measurable physical dimensions of resistance components in natural rivers (e.g. substrate size, vegetation type and density, channel plan form, etc.). More recently, however, Jordanova and James (2007), and Jordanova (2008) developed alternative forms of resistance relationships for conditions of intermediate- and large-scale roughness, described in Chapter 7. Although these equations have not been applied in ecohydraulic studies in South Africa, they are appropriate for conditions commonly found at Reserve sites. Their application is being investigated in research projects using Reserve data collected in southern Africa over the past decade (refer to Section 9.3.6).

The topographical and hydraulic information necessary for uniform flow analysis includes a survey of the cross-sectional profile, stage and water surface gradient, and a discharge measurement (i.e. ‘basic hydraulic information’ as described in Table 9.2). The procedure for synthesising a high-flow rating point (to complement measured data) is as follows:

- Using the surveyed cross-section, compute the geometric parameters required by the resistance equation (typically, cross-sectional flow area and wetted perimeter) for observed and a higher-flow stage.
- Calculate the resistance coefficient/s corresponding to the observed rating/s using the local surveyed water surface gradient/s.
- Based on the resistance coefficient/s for measured flow/s, photographic matching guides (Desai, 2007; Hicks and Mason, 1998; Barnes, 1967), and experience, estimate the flow resistance coefficient for a high-flow stage, where the relative influence of bed resistance is judged to be low (e.g. annual flood level, but at least approximately ten times the height of the substrate elements (Jordanova and James, 2007; Chapter 7).
- Estimate the high-flow energy slope.

- The water surface slope is surveyed both locally for the morphological unit (to estimate the energy slope through the cross-section at the observed flow/s), and also for the site (i.e. over a longer distance to include morphological units of low (e.g. pool) and high (e.g. riffle) gradients – i.e. representative sequences). Generally, as flow increases, local hydraulic controls (e.g. local increase in bed gradient or backup) become drowned-out, and the local slope approaches the mean site value. The premise, therefore, is that the high-flow gradient may be estimated using the following information: surveyed local (morphological unit) low-flow and site slopes, and the regional valley slope (taken from a 1:50,000 topographical map).
- Synthesise a high-flow rating point using the above estimates for flow resistance and energy slope.

A similar procedure is generally not recommended for synthesising rating points for flows lower than observed (low-flow) values. The reason for this is the uncertainty of estimates for low-flow resistance under conditions of large-scale roughness. The favoured methods use measured data, as discussed in the previous section (i.e. surveys of the stage of zero discharge or thalweg).

Non-uniform analyses (spatially explicit 1-D and 2-D models) require ‘boundary conditions’ to be specified at the upstream and/or downstream limits of the modelled region. In modeling software (e.g. HEC-RAS) specification of these conditions requires the assumption of either critical or uniform (also termed ‘normal’) flow, or alternatively, the specification of a rating curve (e.g. Figure 9.8). Rating information is generally not available for this purpose. Furthermore, sites are selected based largely on ecological and geomorphic criteria, and natural hydraulic controls that are necessary to apply critical flow conditions seldom exist over an adequate discharge range – they are likely to be drowned-out at high flows. Therefore, rating information derived by uniform analysis is usually used for the boundary condition in non-uniform flow computations.

Non-uniform flow conditions

Non-uniform flow refers to the condition in which the energy and bed slopes are not equivalent, i.e. depth and velocity vary with distance downstream. Under these conditions, the hydraulic analysis should take account of changes in cross-sectional shape, bed slope and flow resistance. Therefore, multiple spatially-linked cross-sections need to be surveyed, positioned at changes in cross-sectional shape. Generally, for low flows in rivers, non-uniform flow analyses are more appropriate than uniform analyses, particularly at Reserve sites, since flow is rarely, if ever, truly uniform. However, the preferential allocation of resources for more extensive topographical surveys and sophisticated modeling, rather than hydraulic data collection, is debatable. The reasons for this are that non-uniform analyses do not avoid the need to estimate a fundamental variable: flow resistance – undoubtedly the largest source of uncertainty in river hydraulic modeling (Chapter 7). Furthermore, as discussed in the preceding section, non-uniform flow models (1-D and 2-D) require boundary conditions, usually in the form of rating curves derived by uniform flow analysis. Uncertainty in defining boundary conditions has a concomitant effect on the hydraulic modeling, although this reduces with increasing distance from the boundary, where flow resistance and topography become more dominant hydraulic controls. Resource constraints, however, prohibit surveys of extensive river reaches. Finally, if an empirical boundary rating curve is derived from entirely measured data, a non-uniform analysis provides little benefit, since the rating data can equally be collected at a cross-section/s of interest for assessing ecological flows (i.e. the ‘measured rating data’ approach in Figure 9.8 which avoids the need for spatially explicit hydraulic modeling).

Nevertheless, for certain conditions where measured rating data are not available for an adequate range of discharges, non-uniform flow computations are necessary. These include sites where the principal hydraulic control is not channel roughness. Structural controls, both natural (changes in topography, bed slope and resistance) and artificial (e.g. road crossings – where Reserve sites are often selected due to accessibility) require consideration.

The Hydrological Engineering Centre's River Analysis System (HEC-RAS), developed by the Institute for Water Resources (US Army Corps of Engineers) has undoubtedly become the most universally used 1-D hydraulic modeling software for non-uniform and unsteady flows in natural (and artificial) channels. The program has been widely used in South Africa for ecohydraulic studies, and is freely available for download at http://www.hec.asace.army.mil. Comprehensive documentation includes a User and Reference Manual (Brunner, 2008) and Applications Guide (Warner *et al.*, 2008). The software is flexible, and includes the following features: networks, a variety of structures (e.g. bridges and culverts; in-line structures such as embankments, weirs and gates; and lateral structures), off-channel storage areas, ineffective flow areas and levees, and pumps. Other useful features include a graphical interface, cross-sectional interpolation, and customised result tables that may be exported for further analysis. In addition, HEC-RAS utilises a visual database storage system (HEC-DSSVue), designed to efficiently store, retrieve and manipulate typically sequential data such as time series and rating tables – most useful for unsteady flow analyses (Birkhead *et al.*, 2007). The resistance formulation is according to Manning (Chapter 7), and the latest version (4.0) also incorporates sediment transport modeling, water temperature and chemistry.

One-dimensional hydraulic modeling using HEC-RAS (and HEC-DSSVue) was successfully applied to predict the flooding characteristics of the Nyl River floodplain (Birkhead *et al.*, 2004, 2007; James *et al.*, 2004). The floodplain is a world-renowned conservation area and RAMSAR site, located in the Limpopo Province of South Africa, and Figure 9.9 illustrates a reach located in the Nylsvley Nature Reserve. Hydrological (Pitman and Bailey, 2004; Havenga *et al.*, 2007) and hydraulic models of the Nyl River floodplain were developed to provide the means for assessing impacts of future upstream water resource developments. Separate, but linked hydraulic models were defined for three contiguous portions of the large floodplain, some 41 km in extent. An extensive data collection programme ran from 1996 to 2001, and the wettest season was used for model development, with the remaining data used for verification. The models were calibrated through adjustment of the flow resistance for the main channel and floodplain in each portion, and are able to predict flooding characteristics at resolutions appropriate for ecological interpretation, as illustrated in Figure 9.10. Although an ER assessment has not yet been undertaken for the floodplain, model applications (Kleynhans, 2005; Kleynhans *et al.*, 2007a) considered effects of flow regulation on a key indicator of ecological impact: the floodplain vegetation *Oryza longistaminata*, or Wild Rice.

Figure 9-9 **Aerial view of the Nyl River Floodplain in the Nylsvley Nature Reserve (24°38'25''S 28°41'59''E) (*Photograph K. Rogers*)**

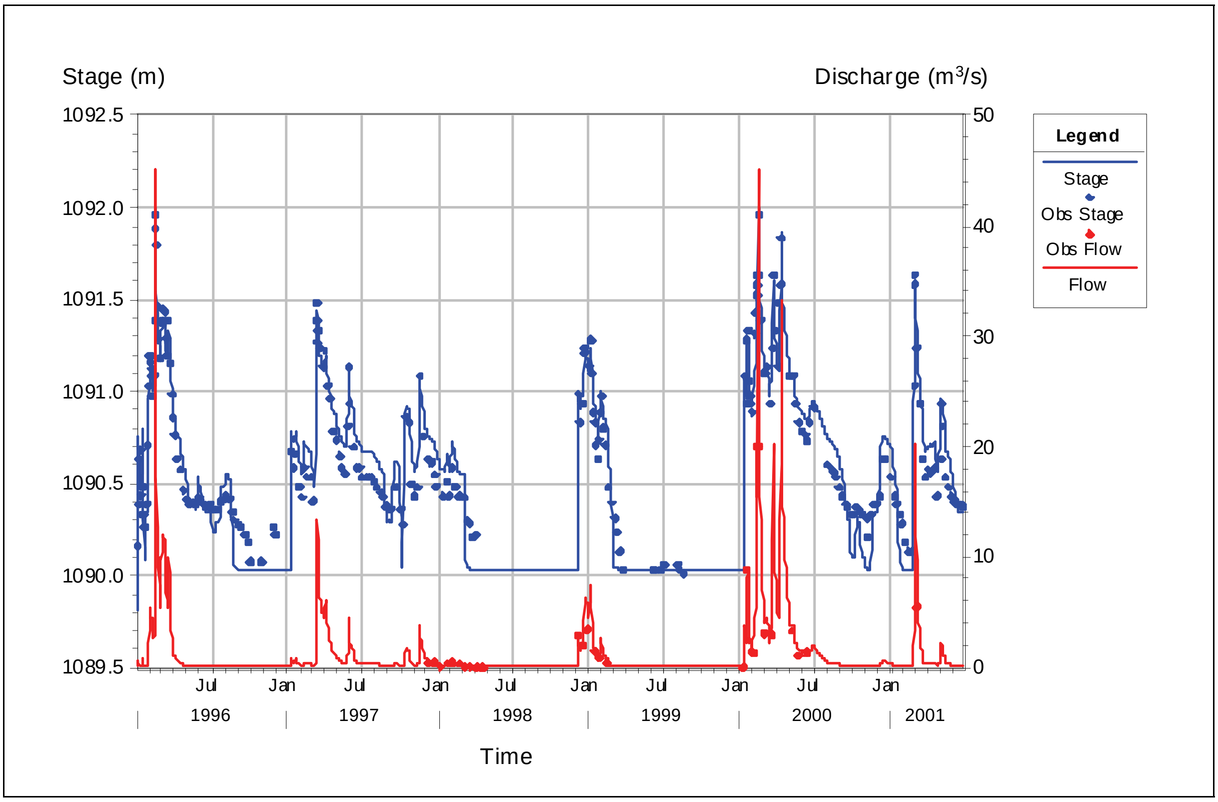


Figure 9-10 **Plot of modelled stage and discharge hydrographs at a location in the Nylsvley Nature Reserve for the period 02/01/1996 to 27/06/2001 (after Birkhead *et al.*, 2007).**

Recently, a river Reserve assessment using HEC-RAS was undertaken for the 11 km reach of the Mokolo River floodplain system illustrated in Figure 9.6. Whereas the Nylsvley study benefited from extensive and high resolution field data (a LIDAR survey providing 1.9 m filtered points, and six years of flow data), the Mokolo study made use of very limited information (seven cross-sections, stage levels for one discharge, and annual peak flood analysis using an upstream gauging station). Despite this, the application was successful in determining, with suitable accuracy for an Intermediate level of assessment, the flows in the Mokolo and Tambotie Rivers that inundate the floodplain. This accuracy was inferred by agreement with indicators of current flooding frequency from geomorphological and vegetation assessments of the floodplain area shown in Figure 9.11. The non-uniform analysis indicated that inundation of the lower Tambotie floodplain (Figure 9.11) results primarily from backup of Mokolo River flows. Results were further analysed (using the HEC-RAS export facility) to provide average values for depth, width and area of inundation. These were necessary for assessing the ecological response of vegetation, fish and invertebrates to flow regulation from the upstream Mokolo Dam.

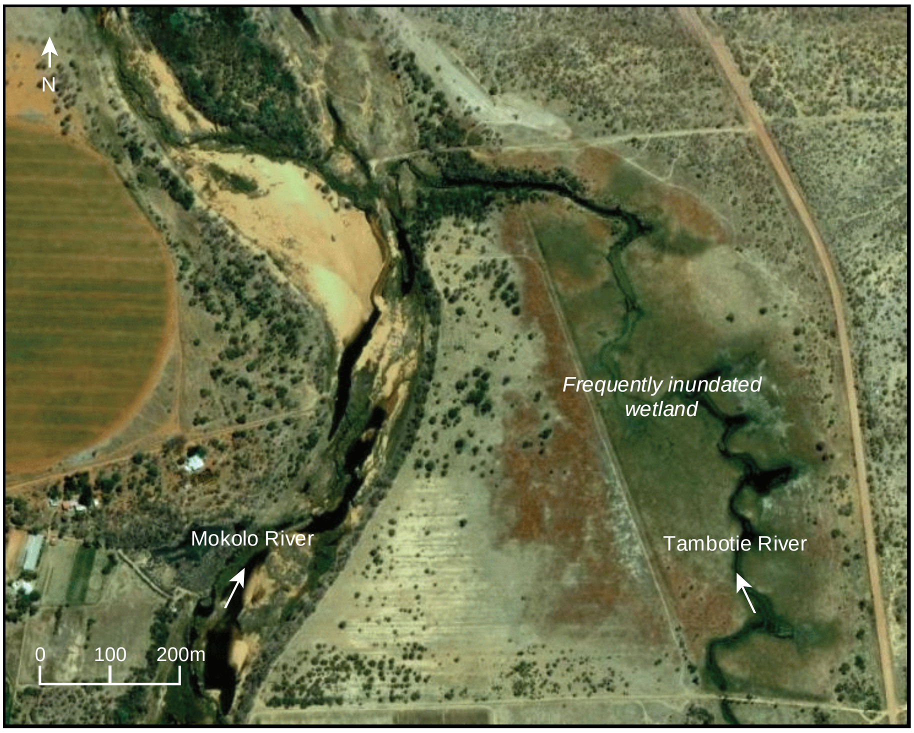


Figure 9-11 Annotated Google^{TM} Earth satellite image of the Mokolo River floodplain system (23°47'38''S 27°46'00''E), showing the frequently inundated lower Tambotie floodplain resulting primarily from backup of Mokolo River flows. Flows in the Mokolo River are highly regulated by an upstream dam

A drawback of 1-D hydraulic analyses is that velocities are treated as average cross-sectional values. Hydraulic descriptions used by river ecologists differ from traditional hydraulic applications: aquatic biota respond to combinations of 'point' values of certain hydraulic variables (Gore *et al.*, 1991; King and Tharme, 1994; Pollard, 2000; Paxton, 2009) and interactions between these and other requirements such as cover and proximity to food and shelter (Hardy *et al.*, 2006; Hirschowitz and Paxton, 2007). For traditional hydraulic (engineering) applications, larger spatial scales (e.g. for flood analysis) have been adequate. It has become increasingly evident during the course of flow assessments in South Africa that average values are inadequate for meaningful ecological interpretation. However, modeling spatial distributions of point hydraulic variables in river reaches at low flows with large resistance elements is imprecise and requires accurate topographical information (Lamouroux, 1998; Section 9.3.4). An alternative method is by enhancing 1-D analyses using spatially explicit distributions of cross-channel velocity, as discussed by Hirschowitz *et al.* (2007), summarised below:

> There are two direct methods of computing lateral velocity distribution, with the most common applications based on the Divided Channel Method (DCM) (e.g. PHABSIM, HEC-RAS, HABITAT, EVHA, and the SORAS module in CASiMIR). The channel is divided (laterally) into zones of varying conveyance with associated different local flow resistances, which are calculated from measured cross-channel velocity distributions. Since cross-channel conveyance is typically a function of flow, velocities should be measured for a range of discharges. This, however, avoids the need to model lateral distributions in the first place, since the actual distributions should be measured! The other is the Lateral Distribution Method (LDM), which is based on the steady-state continuity and momentum equations of motion. According to Webber and Menéndez (2004), the LDM has superior accuracy. The only known software application is the Conveyance Estimation System (CES) developed by Wallingford Software (2004).

There is some scope for applying the above lateral velocity distribution methods in ecohydraulic studies. Typically, however, variance in velocity at Reserve sites arises from localised flow behaviour due to flow obstructions from large substrates and non-uniform (longitudinal) channel topography. This differs from the rationale for velocity variations in the DCM, *viz.* lateral variations in flow resistance (and thus conveyance) associated with cross-sectional shape and channel plan form. These methods are therefore more appropriate to compound channels sections, described in Chapter 7.

Another alternative for providing ecologically relevant point hydraulic parameters is through statistical distributions.

Statistical distributions of hydraulic parameters

A number of empirical models for predicting characteristic probability distributions of hydraulic parameters have been published in the literature. The flow chart in Figure 9.7 indicates where these methods fit into the overall structure of hydraulic model-types (i.e. avoiding the need for 2-D modeling). Jordanova *et al.* (2004) described selected empirical methods relevant to Reserve analyses, with a more extensive review provided by Hirschowitz *et al.* (2007) of methods proposed by different authors for describing spatial distribution characteristics of different hydraulic variables, including the following:

Depth

- Lamouroux (1998)

Velocity

- Dingman (1989)
- Lamouroux *et al.* (1995)
- Azzellino and Vismara (2001)
- Jonker *et al.* (2002)

Velocity-depth

- Stewardson and McMahon (2002)

Shear-stress

- Lamouroux *et al.* (1992)

The review of Hirschowitz *et al.* (2007) includes descriptions of field data on which the models are based, input requirements, model equations and applicability within the context of the Reserve. Since statistical models are integral to the provision of ecologically relevant hydraulic information for Reserve assessments (Figure 9.7), the suitability of the methods is briefly discussed below. Additional detail is given for two of the methods used in Reserve ecohydraulics.

The depth-probability distribution of Lamouroux (1998) has two drawbacks. Firstly, measured depths for model calibration are required (for estimation of a so-called 'shape parameter'), and secondly, it was developed using reach-scale data with mixed morphological units (i.e. pool-riffle sequences). Disaggregated distributions for different units are preferable, since biota display preferences for hydraulic conditions associated with different morphologies. Depth distributions can, however, be computed directly from surveyed cross-sectional geometry and water levels determined from 1-D hydraulic analyses (Section 9.3.5). This implies that variations in cross-sectional depth represent those within the morphological unit.

Lamouroux *et al.* (1992) determined the parameters of a bed shear stress-frequency distribution model using measurements from Fliesswasserstammtisch (FST) hemispheres (Statzner and Müller, 1989). As for the depth distribution model, the bed shear stresses are reach-averaged values, and furthermore, are based on a maximum substrate roughness height of only 26 mm. Although the model is not used in Reserve studies (suitability of hydraulic habitat for aquatic biota has not been directly related to bed shear stress), the approach is an innovative and practical method for estimating near-bed conditions with potential for future application.

Azzellino and Vismara (2001) developed empirical equations for the standard deviation of velocity for four different biotopes (which they termed 'habitat units'). These biotopes were defined by ranges of depth and velocity, and include slow and fast-flowing riffles, and medium-depth and deep pools. Although the biotopes are treated separately, the use of a simpler measure of variance (i.e. standard deviation instead of frequency distributions) results in equations that apply to their specific selection of depth and velocity ranges.

Jonker *et al.* (2002) derived velocity distribution models for rapid/riffle, plane bed and pool morphological units based on cross-sectional measurements. The model input requirements are average cross-sectional velocity and depth, and for the riffle unit median particle size. Although the fit for pool units was good (R^2 = 0.95), this was not the case for the rapid/riffle features (R^2 = 0.57). The accuracy of the predictions was not established using independent field data (not used in model development), and the range of applicability was not defined.

The stochastic model of Stewardson and McMahon (2002) predicts the covariance of point depth and depth-averaged velocity-probability distributions. The authors argue that depth and velocity do not vary randomly throughout a stream reach, but rather exhibit spatial organisation as expressed by the equations of motion. Model requirements include simple measures of channel geometry and hydraulic variables, including depth, width and hydraulic radius, as well as a cross-sectional parameter (which according to the authors, requires further investigation). Although the model shows promise, the following factors have detracted from its application in Reserve ecohydraulic studies:

- Model constants are calibrated using reach data, which undoubtedly incorporate different morphological units.
- The equations of motion used to formulate model parameters assume resistance is due to boundary shear. This is unsuitable for conditions of intermediate- and large-scale roughness, as explained in Chapter 7.
- The ability of the model to describe depth-velocity co-variation appears to be an advantage, since this is a fundamental descriptor of hydraulic habitat for certain aquatic biota (Lamouroux, 1998; Ahmadi-Nedushan *et al.*, 2006). Depth and velocity measurements for rapids and riffles, however, indicate independence at low-flows (Hirschowitz *et al.*, 2007) where parameter estimation is particularly relevant for ecological flow assessment.
- It is difficult to uncouple the covariant depth-velocity frequency distributions.

Based on the available methods for predicting characteristic depth-averaged velocity distributions, the methods of Dingman (1989) and Lamouroux *et al.* (1995) have been proposed for use in South African ecological flow assessments, and are briefly described below (modified from Jordanova *et al.*, 2004 and Hirschowitz *et al.*, 2007):

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

$$F(v) = \left(\frac{v}{V}\right)^c \tag{9.2}$$

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

Although measured cross-sectional velocities confirmed the form of equation (9.2) for idealised, regular and irregular natural channels, the distribution parameters (maximum velocity and shape) could not be related to any measurable variables. Dingman (1989) presents three methods for estimating the shape parameter from measured velocities, and suggests that both this parameter and the maximum velocity are dependent on discharge, with these relationships requiring further investigation. The model is therefore useful where measured velocities are available, but limited in its predictive ability at other flows.

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

Lamouroux *et al.* (1995) developed a useful predictive model with distribution parameters that are related to simple descriptors of hydraulic variables in river reaches. The model is widely used in Reserve studies at all levels of determination using 1-D hydraulic analysis (Figure 9.7).

The data used for model development were collected from 37 river reaches, with depth-averaged velocities determined from three point measurements along the vertical. Point measurements were often found to deviate from theoretical logarithmic profiles (developed based on boundary shear), since both emergent and submerged conditions were considered. This is important, as many contemporary studies apply logarithmic vertical velocity distributions that are invalid for conditions of large (and intermediate) relative roughness (e.g. Jonker *et al.*, 2002; Stewardson and McMahon, 2002; and Dingman, 1989 – the latter study also used power and maximum entropy profiles). The average dominant bed roughness was used, defined by the size of the roughness elements occupying the largest bed proportion. Valid statistical analyses were ensured by weighting measurements (according to area or volume).

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

$$f(x) = s\left(3.33e^{-\frac{x}{0.193}} + 0.117e^{-\left(\frac{x-2.44}{1.73}\right)^2}\right) + (1-s)\left(0.653e^{-\left(\frac{x-1}{0.864}\right)^2}\right) \tag{9.3}$$

in which x is the ratio of depth-averaged to reach velocity, $f(x)$ is the frequency density of velocity ratio x, 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, including the Froude number, relative roughness and width variability. The function based on Froude number (Fr) and relative roughness (k/d) gave a regression coefficient R^2 = 0.75 (equation (9.4)), with width variability adding little further value to prediction of the shape parameter (R^2 = 0.78):

$$s = -0.275 - 0.237\ln(Fr) + 0.274\frac{k}{d} \tag{9.4}$$

in which k is the dominant roughness (m), and d is the mean reach depth (m).

Hirschowitz *et al.* (2007) provide comparisons between measured and modelled distributions for a site on the Driehoeks River (Western Cape Province, South Africa), and conclude that the velocity distribution model of Lamouroux *et al.* (1995) gives good predictions at a site scale, and fair accuracy at a morphological unit scale. Two-dimensional hydraulic analyses provide spatially explicit variations of depth and (depth-averaged) velocity, and are discussed in the next section.

Two-dimensional analyses

Two-dimensional hydraulic analyses account for both longitudinal and lateral flow components, and require 3-D topographical information (Section 9.3.3). The analyses are suitable where lateral flows are appreciable or where sites have divided channels at low flows with different stages or average velocities (Figure 9.12), and where the region of interest is not extensive. A 2-D model nested within a 1-D model is useful for analysing extensive river lengths.

As discussed previously, diversity of hydraulic conditions and hence the suitability for assessing ecological flows increases with hydraulic complexity, which, in turn, is associated with increasingly complex flow patterns. Most 2-D models are based on the St Venant Equations (which neglect vertical velocities and accelerations) and also assume a hydrostatic vertical pressure distribution. This limits accuracy in areas of steep slopes and rapid changes in bed slope (Steffler and Blackburn, 2006), conditions generally associated with rapids and riffles at low flows. It is therefore necessary to assess the value to ecological flow assessments of employing more sophisticated and rigorous methods of analysis (*viz.* 2-D or even 3-D). Kondolf *et al.* (2000) maintain that highly accurate hydraulic modeling may not be feasible for rivers with complex topography, and that it cannot resolve flow patterns at the spatial scales at which fish often respond to the environment.

As already discussed, sites where 1-D analyses can sensibly be applied are favoured for Reserve determination purposes in South Africa, due to resource constraints. For more hydraulically complex sites, the preference is for collection of additional field data rather than more rigorous hydraulic modeling. Additional data are associated with higher level Reserves.

Due to limited data collection in Rapid III assessments, they are best suited to sites with relatively simple hydraulic characteristics (*viz.* horizontal cross-river stage in a single channel, low and uniform flow resistance, uniform flow conditions and a site that is dry at the cessation of flow), which are nonetheless useful for flow assessment. At the Comprehensive level of assessment, 2-D hydraulic modeling may be appropriate where, for example, there is there are no sites suitable for 1-D analysis, or where ecological importance justifies more detailed descriptions and reduced uncertainty. Two-dimensional analyses use more representative topographical information (3-D DTMs) to model spatially-explicit depth and depth-averaged velocity. These are used (through frequency analyses) to provide direct estimates of the composition and abundance of flow classes, as indicated in Figure 9.7. Furthermore, 2-D modeling allows an assessment of depth connectivity, useful for assessing fish passage, but not provided for by cross-sectional profiles and characteristic depth-frequency distributions, as discussed in the previous section.

Hirschowitz *et al.* (2007) provide an assessment of various 2-D hydraulic models with reference to general characteristics, data and their use (topographical, boundary and initial conditions, and hydraulic calibration), and hydraulic limitations (simulation times, flow regime, rapidly-varied flow profiles, wetting and drying, and flow resistance). Based on these considerations, the authors cite the following reasons for selecting River2D (a finite-element hydraulic and habitat simulation model) for local use in ecohydraulic studies.

- River2D is freeware, accessible on the internet for download at http://wwwRiver2D.ualberta.ca/ with supporting documentation (Blackburn and Steffler, 2006; Steffler and Blackburn, 2006; Unterschultz and Blackburn, 2006).
- It is able to model wetting and drying.
- It accounts for localised supercritical flows and transitions between subcritical and supercritical flows, provided that boundary flows are supercritical.
- The program has the capability of nesting spatial scales.
- Habitat evaluation includes IFIM-type suitability curves with weighted usable area.
- Hydraulic variables can be mapped.
- Input and output are in the form of text files, allowing for further analysis.

River2D, developed at the University of Alberta (Canada), is a 2-D depth-averaged finite element hydrodynamic model that has been customised for fish habitat evaluation studies. It comprises three modules relevant to South African conditions, one each for editing bed topography, for generating triangular finite element meshes, and for flow and habitat analyses, mesh editing and refinement. A broad discussion of these is provided by Hirschowitz *et al.* (2007). The programme functionality is discussed with reference to programme versatility, spatial scales, model inputs and parameter estimation (including representation of topography, mesh generation, hydraulic data collection, flow resistance, boundary conditions, and eddy viscosity), differences between measured and modelled data, analysis and evaluation of results, and model sensitivity. Although this detail will not be repeated here, two of the reasons cited for selecting River2D are worthy of further discussion – the recurrent problem of wetting and drying, and the value of nested spatial scales.

As water levels change, areas of the channel become wet or dry, and flows through these areas must be added or removed from the computation in a manner that does not compromise conservation of mass or computational stability (adapted from Wright (2001)). Several methods have been developed to account for this, some of which can accommodate changes within an element (a discrete area within the modelled region), but have difficulties when extending over several elements (Quecedo and Pastor, 2002). In Reserve studies, considerable attention is focussed on the low-flow component of the flow regime, where sites are typically characterised by large roughness elements. This requires the analysis of shallow flows with complex boundaries, which, in turn, produces computational instabilities. Accurate modeling requires detailed topographical surveys and the use of a dense mesh (lattice between elements), since flow through a number of adjacent nodes is required for numerical solutions. Furthermore, meshes may need to be reconstructed for different flows due to changes in the position of boundaries and orientation of streamlines (Panfil and Jacobson (1999)). River2D accounts for wetting and drying by using a continuous water surface that is either above or below bed level, with the sub-surface conditions treated as flow through porous media. Although the wet-dry transition is treated well, velocities at the water's edge may be inaccurate (Hirschowitz *et al.*, 2007).

Two-dimensional modeling may be applied at different spatial scales, depending on the required resolution. For a given resolution, the spatial extent is limited by the maximum number of elements that can realistically be included (due to program limitations and long simulation times). At a coarse resolution, a long river stretch may be modelled, whereas at a fine resolution, only a small section may be analysed. River2D includes the useful capability of nesting spatial scales – a finer resolution may be used where higher accuracy is required, or a modelled region may be extracted and re-analysed at a finer resolution.

River2D was applied by Jordanova and James (2007) to simulate hypothetical, rapidly-varied flow conditions associated with multiple local controls. The results were compared with measured data from flume experiments, and indicated that the model describes these flow conditions realistically, particularly trans-critical flow conditions. The model was also shown to predict velocity-frequency distributions reliably under large-scale roughness. Field verification has also been undertaken for two sites on the Cotter River in Australia (Jordanova and James, 2007) and a site on the Driehoeks River in South Africa (Hirschowitz *et al.*, 2007; Jordanova and James, 2007). Comparative results, particularly with reference to velocity-frequency distributions, confirm the reliable use of River2D for conditions of low flow. In addition, the authors concluded from the Cotter River application that a so-called 'one cross-section approach' can be used to estimate flow classes representative of larger river section, if suitable field data are collected. Hirschowitz *et al.* (2007) also describe an application of River2D to a Reserve site on the Letaba River in the Northern Province of South Africa.

Recently, River2D was applied in a Comprehensive Reserve assessment for sites on the Sabie River (Mpumalanga Province) and Vaal River (Gauteng Province) systems, South Africa. Although hydraulically complex sites such as the Sabie River site (Figures 9.4 and 9.5) would normally be avoided even at the Comprehensive level, this site was selected because of the diverse and critical hydraulic habitat for rheophilic biota associated with such bedrock influenced channel-types, and the availability of LIDAR data. The site's inclusion is necessary given the ecological importance and sensitivity of the Sabie River, a contributing factor being that the Lower Sabie River lies within the Kruger National Park. The LIDAR data (for a low discharge of 1.9 m^3/s) were used with a conventional active channel cross-sectional survey to estimate bed elevations, since LIDAR does not penetrate water (Section 9.3.3). A coarse 2-D model was developed with rating data collected over the discharge range 1.9 m^3/s to 334 m^3/s. The mapped velocity magnitudes for a discharge of 7.8 m^3/s are superimposed on an aerial photograph in Figure 9.5, with the cross-section (as indicated) plotted in Figure 9.12.

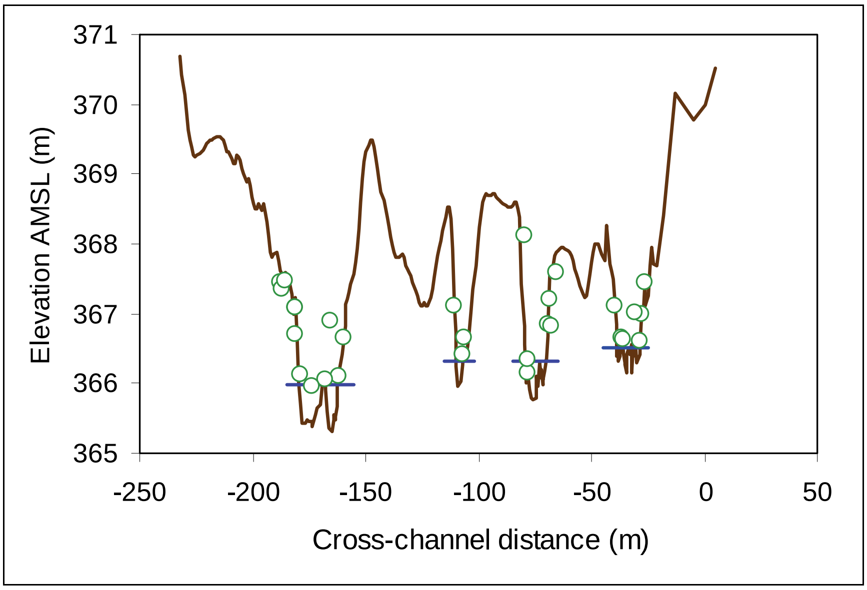


Figure 9-12 The cross-sectional profile through the Sabie River site in Figure 9.4, using 2004 LIDAR data and a conventional survey of the active channel beds. The green markers show the relative positions of indicator species or zones required for assessing inundation levels for riparian vegetation, and the stages are plotted for a discharge of 2.3 m^3/s (AMSL = Above Mean Sea Level).

As mentioned previously, River2D data may be exported in text file format – a useful feature for the post-processing of modelled values for point hydraulic variables (e.g. velocity and shear velocity magnitudes, depth, stage, Froude number). For Reserve analyses using flow classes (refer to Section 9.3.2) this is necessary for statistical analysis of depth-velocity point values as indicated in Figure 9.7. For analyses to be statistically valid, values are best exported using a regular grid. Furthermore, modelled values may also be extracted to text files for any location within the modelled region – a necessary feature for comparing modelled and measured data for selected flows, as well as for extracting hydraulic information, such as rating data.

Basic hydraulic information provided by variables such as depth, velocity, wetted perimeter or inundated area are but components, albeit important ones, of the habitat requirements of aquatic organisms. This information, of a purely hydraulic nature, needs to be expressed in more meaningful terms to assist ecological interpretation for purposes of flow assessment. The contemporary study and application of hydraulics, specifically intended for determining hydraulic conditions at scales occupied by aquatic organisms, or at least to which their response can be related, has led to the concept of 'habitat hydraulics' (NIT, 1994).

9.3.5 Habitat hydraulics

Background

The habitat requirements for biota are often defined as abiotic (physical and chemical) environmental features that are necessary for the survival and persistence of individuals and populations (Armstrong *et al.*, 2003; Rosenfield, 2003). According to Ahmadi-Nedushan *et al.* (2006), the most important physical variables affecting the organisms of running waters include depth, velocity, cover and substrate. Within the aquatic biota (including fish, macro-invertebrates and vegetation) certain taxa display preferences for particular ranges and/or combinations of depth, velocity and bed shear stress (Lamouroux, 1998).

Chapter 4 describes approaches used in South Africa for defining the habitat preferences of aquatic organisms, including Habitat Suitability Criteria (HSC) and the use of more broadly-defined 'flow classes'. These may be combined with hydraulic information to assist with the assessment of ecological flow requirements. Although the IFIM approach using HSC is not used in Reserve assessments, it has received wide international acceptance and application. Consequently, a brief explanation of the method is warranted, together with discussion of its relation to the South African approach and examples of its recent use with 2-D hydraulic modeling.

Habitat Suitability Criteria are expressions of the life stage preferences of species, communities or guilds for specific values of hydraulic and physical variables (e.g. Leonard and Orth, 1988; Lamouroux and Cattanéo, 2002; Lamouroux and Souchon, 2002). Commonly used variables for fish and invertebrates include depth, velocity, cover (for fish) and substrate type, and preferences are generally expressed as indices in the range 0 to 1 (refer to Chapter 4 for details on the development of HSC).

River2D is designed specifically for fish habitat evaluation studies, and includes functionality for using HSC. Here HSC include depth, velocity and 'channel index' variables. The channel index uses numerical values to represent biophysical characteristics such as substrate and vegetation. Hirschowitz *et al.* (2007) recommend the use of reasonably coarse classifications for channel index, including fine and coarse sediments and bedrock for inorganic materials (identical to that proposed by Jordanova *et al.*, 2004), and particulate organic matter, roots and vegetation for vegetation. Using appropriate hydraulic-habitat models (such as PHABSIM or River2D), individual suitabilities (i.e. descriptions of the preference of a particular species, guild, etc. for each variable) are computed for cells (1-D) or nodes (2-D). A Combined Suitability Index (CSI) is obtained by combining these individual suitabilities using different computational options (such as products, geometric means or minima). A measure of the integrated habitat suitability is provided through the well-known Weighted Usable Area (WUA), which is defined as the sum of cell or nodal values. These are, in turn, defined by the product of CSI and the area associated with the node (or proportion of wetted perimeter for a cross-section). Finally, for purposes of flow assessment, a relationship between WUA and discharge is required – broadly, this is the IFIM approach.

The reasons for limited use of the IFIM methodology in South Africa are discussed in Chapter 4. Briefly, they relate to the resource intensive nature of the approach and the historical targeting of individual species although, as already noted, broader guilds or communities may be used. Habitat information for indigenous fish and invertebrates is not well developed in South Africa, with the few detailed published studies including those of Gore *et al*., (1991), King and Tharme (1994), Pollard (2000) and Paxton (2009). The first use of IFIM in South Africa was a study of by Gore *et al*. (1991) of the remaining physical habitat to support endemic fish in the Olifants River (Western Cape Province). More recently, HSC have been used to assess the availability of suitable habitat for three indigenous fish species at a site on the Driehoeks River (Paxton, 2009). The results (Figure 9.13) indicate a high correspondence between the surveyed locations of individuals and the CSI. The model was extended by Hirschowitz and Paxton (2007) to include behavioural aspects for drift-feeding yellowfish (*Labeobarbus capensis*). Behaviour-based models recognise the complex interactions between hydraulic conditions and other habitat requirements of aquatic organisms, particularly proximity to areas providing food or shelter (Hardy *et al.*, 2006). Hirschowitz and Paxton (2007) incorporated these requirements by defining preference ratings for the proximity of adjacent (hydraulic) conditions necessary for drift-feeding. A comparison between results acquired using ‘standard’ suitability criteria, and those from incorporating this behavioural activity are illustrated in Figure 9.14. The results suggest that the standard approach overestimates the quantity of suitable habitat and therefore underestimates flow requirements.

As discussed above, IFIM-type applications using HSC (Figure 9.13) are resource intensive (biologically and hydraulically), and require complex modeling, particularly when behavioural aspects are explicitly accounted for (Figure 9.14). Many South African rivers have low fish species richness and furthermore, many of South Africa's fish species are adapted to naturally harsh environmental conditions (Kleynhans and Engelbrecht, 2000). This means that in certain systems fish are not always good indicators of flow requirements. In these instances it may be necessary to place greater emphasis on the ecosystem requirements of other biota such as invertebrates. Detailed information on habitat preferences for indigenous taxa (including broader fish guilds or invertebrate communities) is generally scarce and generally more limited for invertebrates than for fish.

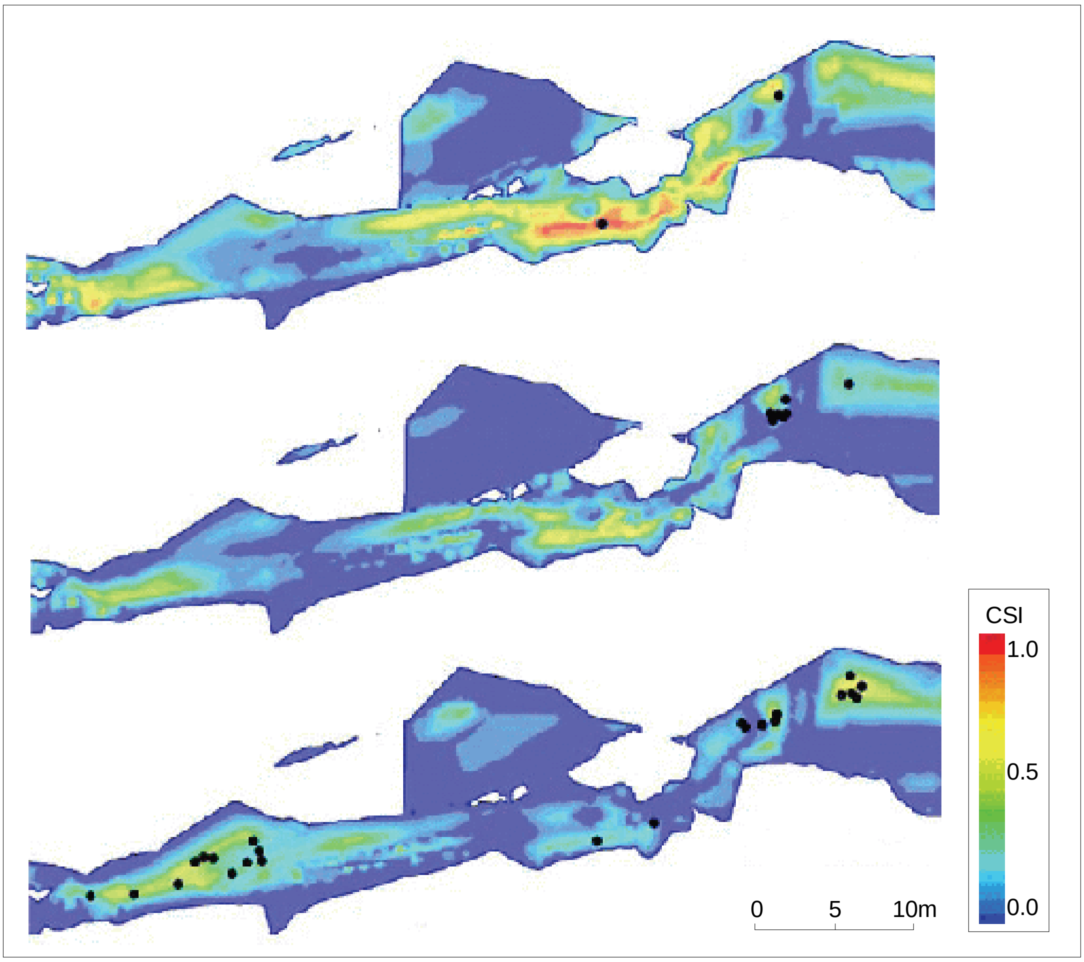


Figure 9-13 **Combined Habitat Suitability Index (CSI) values for a site on the Driehoeks River for (top) spawning sawfin (middle) juvenile yellowfish and (bottom) adult yellowfish. The simulation used River2D and is for a discharge of 0.29 m^3/s. Solid black markers indicate surveyed fish positions and flow is from left to right (after Paxton, 2009)**

Local environmental flow assessments have evolved over the past two decades, from the earliest 'Cape Town' and 'Skukuza' approaches through to the BBM to the more recent HFSR and DRIFT methodologies (Section 9.2.3). Developers of these methodologies have recognised the general lack of detailed habitat-preference information for local aquatic biota, and have therefore sought to provide approaches which align with the understanding of the requirements and responses of flow-dependent biota, and the level of resolution of available information. These holistic methods embody a fundamental objective central to flow assessment in South Africa: the protection of diverse ecosystems in preference to targeting particular species. Hydraulic information therefore needs to be provided in a way that describes the extent and diversity of conditions, at appropriate resolution, and this must be equally true for the various Reserve levels. Early South African (hydraulic) approaches were somewhat deficient in providing ecologically relevant information, and analyses were more suited to traditional high flow applications. Recently, attention has been focussed on habitat hydraulics through research WRC projects (e.g. Jordanova *et al.*, 2004; Jordanova and James, 2007; Hirschowitz *et al.*, 2007) and through ongoing flow assessments (in which method development continues). Collectively, this has resulted in the use of so-called 'flow classes' (refer also to Chapter 4).

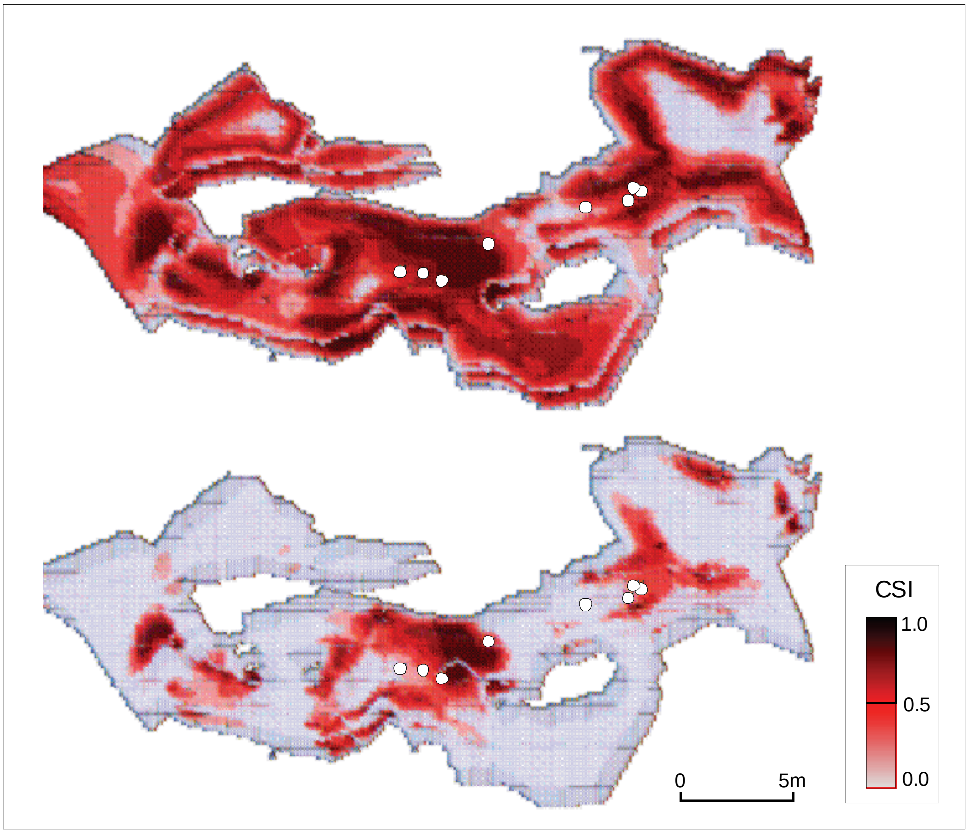


Figure 9-14 **Comparison of Combined Habitat Suitability Index (CSI) values for a site on the Driehoeks River using (top) standard suitability criteria, and (bottom) incorporating drift-feeding behaviour for juvenile yellowfish. The simulation used River2D and is for a discharge of 0.24 m^3/s. Markers indicate surveyed fish positions and flow direction is from left to right (after Hirschowitz and Paxton, 2007).**

Flow classes

Biota in the aquatic environment are associated with a combination of hydraulic variables (e.g. depth and velocity), as well as physical features such as substrate, vegetation and cover for fish. Flow classes are a means of grouping these combinations into units which have ecological meaning, in that they represent broad, known (or 'judged') preferences of biota for hydraulic and biophysical variables. A flow class represents a range of values pertaining to at least two environmental variables, of which at least one is flow-dependent (depth, velocity, area of inundation, etc). Flow classes do not necessarily represent suitability criteria.

In the South African approach to flow assessment, the availability and abundance of suitable flow classes is considered together with other aspects of habitat (including cover, lateral and longitudinal connectivity, food availability, temperature, light, oxygen saturation, nutrient concentration), for different life stages (breeding, spawning, and migrating in the case of fish).

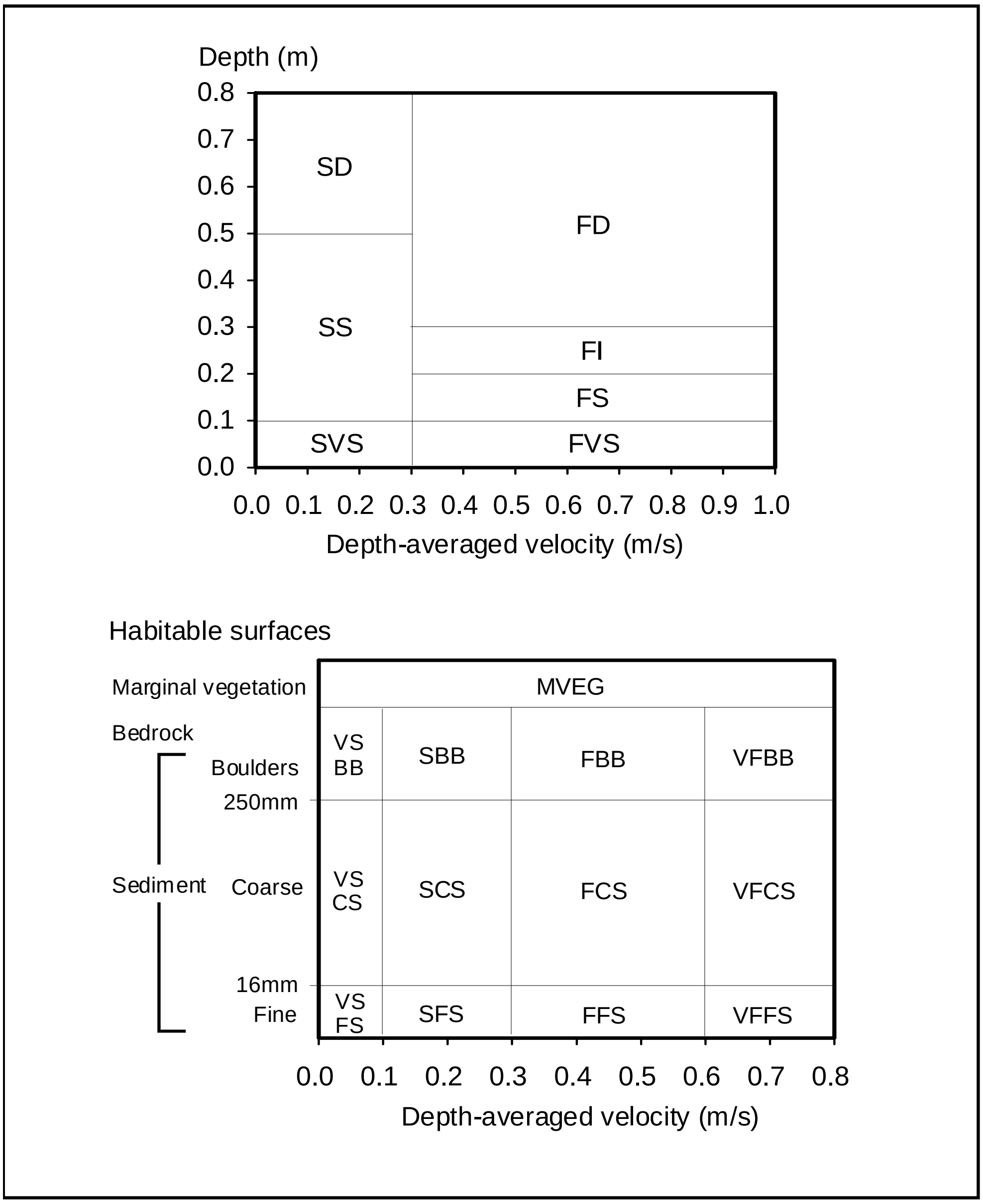
Flow classes (more specifically velocity-depth classes for fish) use preference ratings. These have been determined for some 137 fish species (indigenous and alien), and form part of the Fish Response Assessment Index (FRAI) developed by Kleynhans (2007). The ratings are largely based on expert opinion from a diverse number of specialists, and in this form the (rated) flow classes represent suitability criteria. A similar, broad-based rating system has been initiated for invertebrate families and forms part of the Macro-Invertebrate Response Assessment Index (MIRAI) (Thirion, 2007). Kleynhans (1999) suggested that the hydraulic variables of depth-averaged velocity and depth, together with substrate and cover, may be used to broadly characterise fish habitat. Furthermore, velocity and depth need only be specified coarsely, and four velocity-depth classes were proposed, as adapted from Oswood and Barber (1982) and described in Chapter 4. Recently, development of the principles of a process for extrapolating and/or estimating environmental flow requirements at the desktop-level, by Kleynhans *et al*. (2008), has indicated the need for additional depth categories to give the seven flow classes illustrated in Figure 9.15. This refinement illustrates the important point that the environmental variables used (hydraulic and biophysical) and their numerical ranges may be (re)defined using available information on conditions utilised by indicator biota that is available and relevant to the flow assessment. For example, Lamouroux *et al*. (1999) (cited by Hirschowitz *et al.*, 2007) developed regional habitat preferences for 24 fish species using five velocity classes (*viz*. 0-0.05 m/s, 0.05-0.2 m/s, 0.2-0.4 m/s, 0.4-0.8 m/s, and >0.8 m/s), four depth classes (*viz*. 0-0.2 m, 0.2-0.4 m, 0.4-0.8 m and >0.8 m) and five classes of dominant roughness (*viz*. 0-0.016 m, 0.016-0.064 m, 0.064-0.256 m, >0.256 m and large bedrocks). For rock catfish of the Senquyane River (Lesotho, southern Africa) Niehaus *et al.* (1997) found a velocity of 0.1 m/s to be the threshold separating recruits (lower values) from juveniles and adults (higher values). Cambray *et al.* (1989) noted that the fish species *Barbus afer* and *Kneria auriculata* spawn at depths of 0.1 m to 0.2 m. Such data are ostensibly built into the preference ratings for local fish species. Where detailed preference information exists (e.g. Paxton, 2009) flow classes may be appropriately defined using suitable variables and resolutions.

Furthermore the use of collective ‘groups’ of biota as indicators of flow requirements, as applied by Kleynhans *et al.* (2008) in the development of principles for flow estimation at the desktop level, is well supported in the literature (Leonard and Orth, 1988; King and Schael, 2001; Lamouroux and Cattanéo, 2006, Lamouroux and Souchon, 2002). The use of flow classes and collective indicator groups underlies an important rationale of South African flow assessment: that available information and current understanding establish appropriate resolutions and methodologies, and not *vice-versa*.

Box 9.5

Collective ‘groups’ of biota

Collective ‘groups’ of biota that exploit the same class of environmental resources in a similar way are referred to as a fish ‘guild’ or a ‘community’ in the case of invertebrates. An example are rheophilics, which require perennial flow and very often, fast flow.
http://www.cnr.colostate.edu/~brett/fw300/ flashcrd/defn.htm



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

Figure 9-15 (top) Flow classes for fish (or velocity-depth classes), modified from Jordanova *et al.* (2004). (bottom) Flow classes for invertebrates, modified from Hirschowitz *et al.* (2007). (The velocity and depth axes are truncated for plotting purposes.)

The key variable used for characterising hydraulic conditions for invertebrates is depth-averaged velocity. This, together with substrate type and inundated vegetation have been used to define the important flow classes (Chapter 4). As discussed previously, numerical ranges (and variables) should not be considered fixed, but defined for the organisms being used as indicators of flow requirements. Presently, four velocity classes have been defined for macro-invertebrates: <0.1 m/s, 0.1-0.3 m/s, 0.3-0.6 m/s and >0.6 m/s – efining very slow (VS), slow (S), fast (F) and very fast (VF), respectively. Each of these is associated with three substrate types, providing twelve flow classes characterising conditions for the velocity-substrate domain. The substrate types include fine sediment (FS), coarse sediment (CS), and large boulders/bedrock (BB), since it is recognised that large gravel and loose cobbles usually provide better substrate conditions than large boulders and bedrock (Jordanova *et al.*, 2004) (refer to Section 9.3.3 for sediment size definitions). High velocities over fine substrates (such as sands and smaller grained sediments) generally provide unsuitable conditions due to bed mobility, but are included so that the entire velocity-substrate domain is accounted for. The flow class approach is identical to that identified by King and Shael (2001), where coarse groupings for velocity (slow, moderate or fast) and substrate type (boulder/bedrock, large cobble, pebble, etc.) were found to be associated with unique invertebrate communities, as discussed in Chapter 4. These are also similar to the qualitative descriptions for sampled habitats used in SASS (e.g. 'stones in current'). As already mentioned, however, for predictive purposes, use of qualitative descriptions such as 'fast' or 'current' requires numerical quantification.

Marginal and aquatic vegetation also provide important habitat for certain invertebrates, particularly in rivers with highly mobile beds as illustrated by the run in Figure 9.3. Development of a generic and reliable approach for modeling vegetation-influenced flow that is suitable for hydraulic analysis at all Reserve levels (Table 9.2) has not been successful. This is due to the typically complex spatial-distribution of vegetation in natural river channels, as illustrated in Figure 9.16, further complicated by the variety of vegetation types (such as reeds, sedges, grass, and any overhanging vegetation). Presently, 2-D hydraulic analyses probably provide the most reliable method for predicting velocities adjacent to vegetation in rivers, with velocities at the clear-flow/vegetation interface and through the vegetation estimated using procedures described in Chapter 7. Hirschowitz and James (in press) have also presented a non-computational method for describing the transverse distribution of velocity in channels with emergent bank vegetation. Only the extent of inundated vegetation is estimated (based on field mapping), and there is no further sub-division of the flow class using velocity ranges. These thirteen flow classes are used to characterise the hydraulic habitat for invertebrates.

As mentioned previously, flow class definitions may change depending on the indicator biota used, and also with new research results on the habitat preferences of aquatic organisms. With this in mind, a simulation model was developed to support (1-D uniform flow) hydraulic analyses, using flow classes for expressing hydraulic information in terms suitable for ecological interpretation (Figure 9.7).

The Habitat-Flow simulation model (HABFLO)

The habitat-flow simulation model, HABFLO, is designed to provide flow-dependent, ecologically relevant, hydraulic information for all levels of Reserve requiring site-specific data. The model is described by Hirschowitz *et al.* (2007) with an explanation of assumptions and approximations, a definition of flow classes, model structure, statistical frequency-distributions, velocity correction, analysis of depth and velocity measurements, data requirements and results. For ease of reference, important fundamentals are briefly described below:

Figure 9-16 Complex arrangements of marginal and instream vegetation: (top left) reeds (*Phragmites maritianus*) in a bedrock rapid, (top right) sedges (*Cyperus marginatus*) in a cobble/boulder riffle; (bottom) riparian and overhanging marginal vegetation along a river's banks

Model assumptions

HABFLO is based on the following assumptions:

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

The requirement for cross-sections to represent the characteristics (topographical and hydraulic) of morphological units has been discussed in the selection of field sites and 1-D hydraulic analyses (Sections 9.3.3 and 9.3.4, respectively). The suitability of empirical methods is discussed in Section 9.3.4, and includes limited predictive ability and the use of reach-scale model development for the Dingman (1989) and Lamouroux *et al.* (1995) models, respectively. However, comparisons between measured and modelled distributions indicate that the latter model provides good predictions at the site scale, and fair predictions at the morphological unit scale (Hirschowitz *et al.*, 2007). Furthermore, since critical conditions for flow-sensitive biota are generally associated with riffles and rapids, use of a reach-scale model for the unit-scale will increasingly underestimate lower velocities and will therefore be conservative for flow assessment purposes. The third assumption requires discussion, since it underlies the use of statistical distributions.

Measurement of point depths and depth-averaged velocities in rapids and riffles has indicated independence at low-flows (Hirschowitz *et al.*, 2007), where parameter estimation is particularly relevant for ecological flow assessment. This appears contrary to the work of Stewardson and McMahon (2002), where depth and depth-averaged velocity were treated as covariant parameters exhibiting spatial organisation assumed to be expressed by the equations of motion. The apparent difference is likely due to the assumption of boundary friction controlled conditions, whereas for large-scale roughness, flow resistance is dominated by form drag (Chapter 7; Jordanova and James (2007)). Assuming, therefore, that depth and depth-averaged velocity are mutually exclusive parameters, the joint probability of occurrence is given by the product of individual values. Likewise, velocity and substrate-type are assumed to be independent variables. Although this is reasonable for sites with poorly-sorted sediments (typical of rapids and riffles, Figure 9.4,), local hydraulic conditions may result in well-sorted sediments displaying spatial organisation, which is difficult to model generically.

If these assumptions, necessary for the modeling approach developed, are unacceptable due to site conditions, two alternatives exist. The first involves the collection of field data over a wide range of discharges (i.e. the largely empirical approach in Figure 9.7), and the second is 2-D hydraulic modeling with the necessary data collection (i.e. the more rigorous computational modeling approach). Since the lower level ER estimations do not support either of these options to provide basic hydraulic information, the only practical alternatives are selecting suitable Reserve sites (as described in Section 3.3.1) or accepting the level of uncertainty associated with relatively simplistic hydraulic modeling at complex sites.

Velocity correction

Assuming that depth and depth-averaged velocity are independent variables (i.e. they vary randomly), then for a given depth, an estimate of discharge is provided by

$$Q = W\sum yvF(y)F(v) \tag{9.5}$$

where W is the inundated channel width (m), y is the depth (m) with frequency of occurrence $F(y)$, and v is the depth-averaged velocity (m/s) with frequency of occurrence $F(v)$.

The depth-frequency and velocity-frequency distributions in equation (9.5) are derived from a surveyed cross-sectional profile and statistical models (equation (9.2) or equations (9.3) and 9.4)), respectively. The relationship between depth and average cross-sectional velocity is provided from the continuous rating function (equation (9.1)) or a resistance equation (as provided in Chapter 7), its accuracy depending on the range of field measurements and site characteristics. The discharge estimate provided using rating data is of higher confidence than that predicted from equation (9.5), and the former may therefore be used to correct the velocity prediction in equation (9.5). This is achieved by scaling the velocities, whilst maintaining the frequency distribution. Model testing using the Lamouroux *et al.* (1995) distribution has produced correction factors in the range 0.80-0.95 (Hirschowitz *et al.*, 2007), implying a difference of only 5-20%. This supports the assumption of velocity-depth independence at low flows in rapids and riffles.

Analysis of measured depth and velocity data

Measured depth and (depth-averaged) velocity distributions provide useful comparisons with modelled distributions, but are of limited predictive value since they correspond to isolated discharge values. If velocity measurements are available for selected discharges, the Dingman (1989) distribution (equation (9.2)) may be used, with the shape parameter derived from measurements. The maximum velocity may be estimated from the Lamouroux *et al.* (1995) distribution or through user-defined values. Generally, insufficient velocity data are available for this purpose and the latter distribution is applied.

Data requirements

The model requires at least the following data:

- Cross-sectional profile (Section 9.3.3).
- Hydraulic data, including rating data with corresponding energy slopes and resistance coefficients.
- Rating coefficients in equation (9.1); these may be computed directly from two rating points assuming the depth of zero discharge (c) is zero (i.e. Rapid III-type analysis).
- Dominant roughness (k) in equation (9.4).
- Numerical ranges of hydraulic variables defining fish (depth and velocity) and invertebrate (velocity) flow classes (Section 9.3.5).
- For the latter, the proportional composition of substrate categories as well as the topographical position and height of marginal vegetation (data collection is described in Section 9.3.3).

The resistance formulation used is the Manning equation, although future model versions may include the alternative equations more appropriate for intermediate- and large-scale roughness, as proposed by James and Jordanova, 2007 (Chapter 7). Rating data may include a combination of measured and synthesised values, with a continuous function (equation (9.1)) describing the depth-discharge relationship. Extrapolation of the function may infer unrealistic resistance coefficients at low flows, favouring the alternative use of the resistance equation with estimated coefficients.

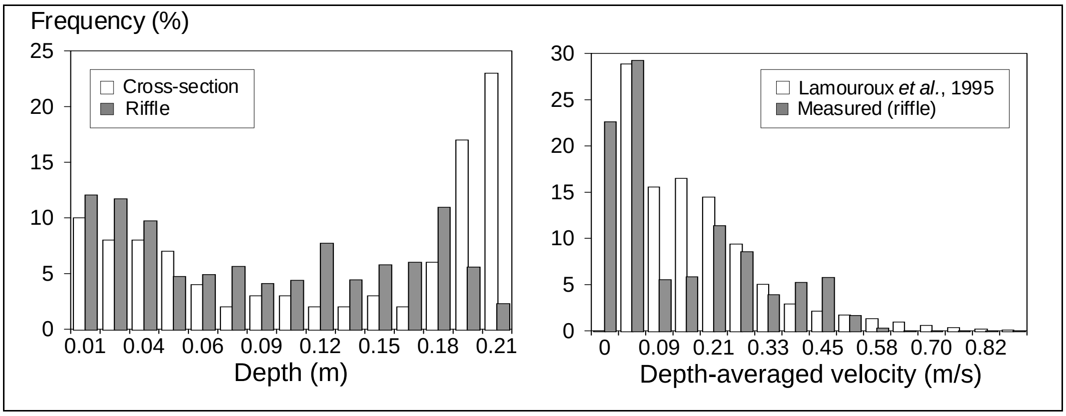
Results

Results of HABFLO simulations include a text file (e.g. Table 9.3 for a particular morphological unit) relating discharge to ecologically relevant hydraulic parameters, *viz*. maximum and average depth, width, perimeter, average and maximum (99.5% on Lamouroux *et al*., 1995 distribution) velocity, as well as the relative spatial composition of hydraulic/biophysical conditions defined using flow classes for fish and invertebrates (refer to Figure 9.15 for abbreviations). Other results include modelled (and measured if available) frequency distributions of depth and velocity as functions of discharge and a resistance computation file.

Table 9-3 Modelled hydraulic data and flow classes using basic hydraulic analyses indicated in Table 9.2

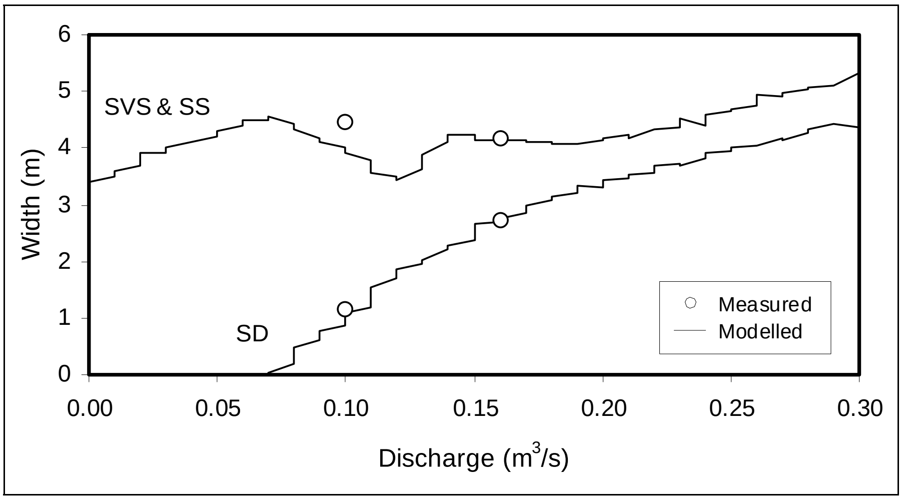
Hydraulic variables							**Flow classes (% spatial composition)**																			
Max. depth (m)	Ave. depth (m)	Discharge (m^3/s)	Width (m)	Perimeter (m)	Velocity (m/s)		**Fish velocity-depth classes**							**Invertebrates**												
					Ave.	Max.	SVS	SS	SD	FVS	FS	FI	FD	VSFS	SFS	FFS	VFFS	VSCS	SCS	FCS	VFCS	VSBB	SBB	FBB	VFBB	MVEG
0.02	0.01	0.000	0.1	0.1	0.02	0.08	100	0	0	0	0	0	0	30	0	0	0	10	0	0	0	60	0	0	0	0
0.04	0.02	0.000	0.1	0.2	0.04	0.13	100	0	0	0	0	0	0	28	2	0	0	9	1	0	0	56	4	0	0	0
0.06	0.03	0.000	0.2	0.2	0.05	0.17	100	0	0	0	0	0	0	26	4	0	0	9	1	0	0	52	8	0	0	0
0.08	0.04	0.001	0.3	0.3	0.06	0.21	100	0	0	0	0	0	0	24	6	0	0	8	2	0	0	48	12	0	0	0
0.10	0.03	0.001	0.5	0.6	0.06	0.20	100	0	0	0	0	0	0	25	5	0	0	8	2	0	0	50	10	0	0	0
0.12	0.04	0.002	0.8	1.0	0.06	0.22	93	7	0	0	0	0	0	24	6	0	0	8	2	0	0	48	12	0	0	0
0.14	0.04	0.004	1.3	1.4	0.07	0.25	90	10	0	1	0	0	0	22	7	0	0	7	2	0	0	47	15	0	0	0
0.16	0.04	0.006	1.9	2.2	0.08	0.26	90	9	0	1	0	0	0	22	8	0	0	7	3	0	0	44	16	0	0	0
0.18	0.05	0.011	2.5	2.8	0.09	0.30	88	10	0	2	0	0	0	20	10	1	0	7	3	0	0	38	19	2	0	0
0.20	0.06	0.018	3.0	3.4	0.10	0.34	79	17	0	4	1	0	0	18	11	1	0	6	4	0	0	36	22	2	0	0
0.22	0.07	0.028	3.4	3.9	0.11	0.38	70	24	0	5	2	0	0	16	12	2	0	5	4	1	0	32	24	4	0	0
0.24	0.09	0.040	3.8	4.3	0.13	0.44	61	31	0	6	3	0	0	15	13	3	0	5	4	1	0	29	25	6	0	0
0.26	0.10	0.055	4.2	4.8	0.14	0.46	48	42	0	5	4	0	0	14	13	3	0	5	4	1	0	28	26	6	0	0
0.28	0.11	0.072	4.6	5.3	0.15	0.51	41	48	0	5	6	1	0	13	13	3	0	4	4	1	0	28	28	6	0	0
0.30	0.12	0.094	5.0	5.8	0.16	0.55	34	52	0	6	7	1	0	12	14	4	0	4	5	1	0	24	28	8	0	0
0.32	0.13	0.12	5.5	6.4	0.17	0.59	32	52	0	6	7	2	0	12	14	4	1	4	5	1	0	23	27	8	2	0
0.34	0.13	0.15	6.1	7.1	0.18	0.61	32	50	0	7	7	3	0	11	13	5	1	4	4	2	0	22	26	10	2	0
0.36	0.14	0.18	6.7	7.8	0.19	0.64	31	49	0	8	7	5	1	11	13	5	1	4	4	2	0	22	26	10	2	0
0.38	0.15	0.22	7.2	8.4	0.20	0.68	27	50	0	8	7	7	1	10	13	5	1	3	4	2	0	21	27	11	2	1
0.40	0.16	0.26	7.7	9.0	0.21	0.71	26	50	0	8	6	8	2	10	13	6	1	3	4	2	0	20	26	12	2	1
0.42	0.17	0.31	8.2	9.6	0.23	0.74	22	50	0	9	7	8	3	9	12	6	2	3	4	2	1	18	24	12	4	2
0.44	0.18	0.37	8.7	10.2	0.24	0.79	20	49	0	9	8	9	5	9	11	7	2	3	4	2	1	18	22	14	4	3
0.46	0.19	0.44	9.2	10.8	0.25	0.84	18	47	0	10	9	8	7	8	11	8	2	3	4	3	1	15	21	15	4	4
0.48	0.19	0.51	9.9	11.7	0.26	0.84	17	48	0	9	9	7	10	8	11	8	2	3	4	3	1	15	21	15	4	5
0.50	0.20	0.60	10.6	12.5	0.28	0.92	16	44	0	11	10	7	11	7	10	8	2	3	3	3	1	15	21	17	4	5

Modelled (cross-sectional) and measured (in a riffle) depth and velocity frequency distributions for a site on the Driehoeks River are shown in Figure 9.17, and flow classes for a run are plotted in Figure 9.18. For the purpose of ecological flow assessment, hydraulic information needs to be expressed over the discharge continuum, as illustrated in Figure 9.18, whereas few isolated measurements at different discharges have limited predictive potential, as discussed in Chapter 4 with reference to the mapping of biotopes and surface flow types.



Note: discharge = 0.10 m^3/s; average depths = 0.12 and 0.09 m and depth-averaged velocities = 0.17 and 0.14 m^3/s for the cross-section and riffle, respectively; maximum depth-averaged velocity (measured, riffle) = 0.65 m/s and modelled = 0.72 m/s at 99.5%

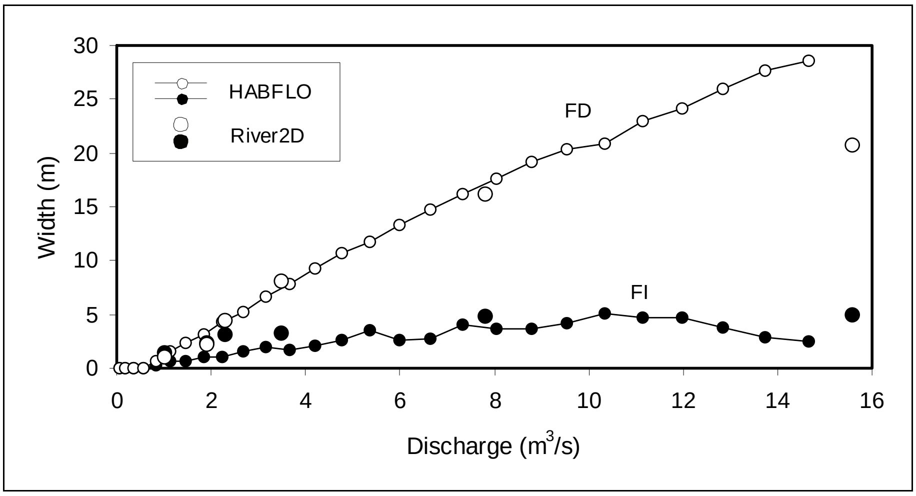
Figure 9-17 (left) Measured depth-frequency distributions for a representative cross-section and for the riffle unit on the Driehoeks River; (right) measured and modelled (Lamouroux *et al.*, 1995) frequency-velocity distributions



Note: SVS=slow/very shallow; SS=slow/shallow; SD=slow/deep

Figure 9-18 Modelled (HABFLO) and measured abundance of flow classes, expressed using channel width, for a run at a site on the Driehoeks River; refer to Figure 9-15 for flow class velocity and depth ranges

Two important velocity-depth classes for assessing flow requirements for rheophilic fish at the Sabie River site (Figures 9.4, 9.5 and 9.12) are fast/intermediate (FI) and fast/deep (FD). These were modelled using 1-D (HABFLO) and 2-D (River2D) analyses, and the results plotted in Figure 9.19. Given that a site of this complexity would usually not be selected for 1-D uniform flow analysis, the results compare surprisingly well for this complex site over the low-flow range (although the cross-sectional profile (Figure 9.12) was used to infer bed levels for use in the 2-D modeling).



Note: FI=fast/intermediate and FD=fast/deep

Figure 9.19 **Modelled (HABFLO: 1-D uniform, and River2D: 2-D non-uniform) abundance of important hydraulic habitats for rheophilic fish for a site on the Sabie River, expressed using channel width. (Refer to Figure 9-15 for flow class velocity and depth ranges)**

9.3.6 Future developments

As is evident from this chapter, theoretical hydraulic modeling is well developed and software is freely accessible for 1-D and 2-D analyses. Reliable estimation of certain model parameters, such as flow resistance (as described in Chapter 7) and eddy-viscosity (required for 2-D modeling) as well as statistical depth- and velocity-frequency distributions, remains difficult, however. Compared with the study of open channel flow (Aristotle is credited with the notion of flow resistance in the 4th Century BC, while modern concepts date from Cheźy in the latter part of the 18th Century), published studies of the hydraulic habitat requirements of aquatic organisms are few, and very recent in South Africa (*viz*. Gore *et al.*, 1991; King and Tharme, 1994; Pollard, 2000; King and Schael, 2001; and Paxton, 2009). Reliable assessment of ecological flow requirements therefore requires continued basic research on the relationships between aquatic biota and hydraulic conditions, as described in Chapter 4.

In South Africa, there is a pressing need to implement Reserves for the equitable (re)allocation of water resources, considering both ecological requirements and human demands. This is addressed through IWRM, which involves hydrological modeling using hydronodes (points of interest where EWRs are required), few of which are Reserve sites. To support this, principles of extrapolation (from Reserve sites) and desktop-type estimation are required. The Desktop Reserve model (Hughes and Münster, 2000) is the most cost-effective method for estimating ecological flows in South Africa, and is increasingly used locally and internationally, to assist water resource planning. The model provides low-confidence estimates based on empirical relationships between the proportion of natural runoff and hydrological characteristics, for a given river condition. To improve confidence, ecological and ecohydraulic components require development (Birkhead and Kleynhans, 2008).

Following Reserve implementation, monitoring is required to assess whether ecological objectives are being attained. Reserve monitoring involves an assessment of hydraulic and biophysical conditions, requiring the development of appropriate survey techniques and methods of analysis.

In summary, the application of ecohydraulics in ERs will benefit from developments in the following areas:

- ***Resistance estimation***. Specifically, field testing of the relationships for intermediate- and large-scale roughness as proposed by Jordanova and James (2007) and described in Chapter 7.
- ***Statistical frequency-distribution methods***. Further testing of existing reach-scale models and development (using 2-D hydraulic modeling) of morphological unit-scale methods for use in Reserve assessments. The extensive flume data of Jordanova and James (2007) may be valuable for model development.
- ***Habitat Suitability Criteria***. Detailed studies of the hydraulic habitat requirements of aquatic biota, for informing the modeling of habitat hydraulics (e.g. the description of flow classes).
- ***Refinement of the Desktop Reserve model***. Further development of the Desktop Reserve model to explicitly predict hydraulic conditions, flow indicator taxa and associated preferences for hydraulic habitat as a function of river condition.
- ***Reserve monitoring***. Development of appropriate techniques for assessing hydraulic and biophysical condition following Reserve implementation.

A number of these areas (*viz*. resistance estimation; hydraulic habitat requirements of invertebrates; refinement of the Desktop Reserve model and Reserve monitoring) are being addressed in concurrent studies commissioned by the Water Research Commission and Department of Water Affairs and Forestry. The science of environmental flow assessments is young, and the true test of managing flows successfully to meet ecological objectives is through ecological monitoring. Based on this, some methods will be discarded, others refined, and probably more developed! Meanwhile, the role of ecohydraulics will continue to evolve in parallel with this process.

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Notation

a:	coefficient in stage-discharge relationship
b:	coefficient in stage-discharge relationship
c:	coefficient in stage-discharge relationship, water level at zero discharge
c:	shape parameter in velocity probability distribution
d:	mean reach flow depth
k:	dominant bed roughness
$F(v)$:	frequency of occurrence depth-averaged velocity
$F(y)$:	frequency of occurrence of flow depth
Fr:	Froude Number
Q:	discharge
s:	shape parameter in velocity probability distribution
V:	maximum velocity in cross section
v:	local velocity
v:	depth-averaged velocity
W:	inundated channel width
x:	ratio of depth-averaged to reach velocity
y:	maximum flow depth

10. RIVER REHABILITATION AND IMPACT MITIGATION STRUCTURES

MT Kleynhans, B Abban and MJ Shand

10.1 Introduction

In the past, traditional engineering approaches had little concern for the adverse ecological effects associated with altering riverine ecosystems. Rivers have been degraded historically due to practices such as channelisation, canalisation and in-stream mining that change bed substrates, local flow and sediment regimes resulting in a reduction in the diversity of flow and aquatic habitats. Anthropogenic activities in the catchment such as agriculture and invasion of areas by alien vegetation, as well as engineering practices such as surface and groundwater abstraction, dam construction, regulation of stream flow, effluent discharge into streams and inter-basin transfers all modify the flow and sediment regimes by affecting the timing and quantity of runoff and streamflow. This leads to changes in channel morphology, water quality and consequently biota. Increased awareness in more recent times has led to the recognition of the ecological importance of rivers by the engineering fraternity and of the need to rehabilitate degraded rivers and to design new river engineering works in a sustainable and ecologically friendly manner.

Various terms are used in the literature to describe the deliberate improvement of a degraded river ecosystem (King *et al.*, 2003; Uys, 2003). According to King *et al.* (2003) there is no consensus internationally about what is meant by river rehabilitation as opposed to river restoration. The two terms are used loosely to describe a variety of projects with different goals and the ambiguity is largely as a result of the value that different people place on the natural environment and what is considered to constitute a natural environment. According to Uys (2003), the term restoration implies the return to a natural pre-impact state and is thus aspirational and seldom achievable; rehabilitation focuses on achievable objectives and also aims for improvement and protection with the aim of the ecosystem eventually resembling its pre-impact state; remediation aims to improve the ecological condition of the river while not aiming for an endpoint that resembles its original condition. Quinn (2003) defines reclamation as aiming to adapt an ecosystem to suit a specific human purpose which may or may not be consistent with its ecological functioning and may not resemble its pre-impact state. According to King *et al.* (2003), whichever view is held, there is generally a common goal of desiring to return a degraded ecosystem to a more natural state. The term ‘river rehabilitation’ will be used in this Chapter, as Uys (2004a) reports that this term is gaining favour within Australia and Britain, and in recognition of the fact that the aim is to improve the state of the river as much as is possible, to a state that resembles its pre-impact state, but within practical limits.

Unfortunately, Uys (2004a) reports that river rehabilitation projects in South Africa are still relatively *ad hoc*. She reports that poor definition of the terminology leads to a perception that engineering projects focussed on storm-water management, flood control or remediation constitute rehabilitation efforts when in fact they may not. In South Africa, no comprehensive guidelines for river rehabilitation are yet available, and this was identified by Uys (2004a) as an important topic for future research.

Earlier Chapters have explained how the availability of suitable hydraulic habitat in rivers is determined by the occurrence of water within a physical template, defined by the channel morphology. The channel morphology is itself a product of the dynamics of sediment and water within a geological structure. River health therefore depends on the water and sediment supply regimes and a compatible channel form. This Chapter describes these dependencies and their implications for rehabilitation in two distinct parts. Section 10.2 presents the fundamental impacts on river health caused by disturbances to the supply regimes and channel form, and rehabilitation measures for implementation on a local to reach scale. Section 10.3 describes major hydraulic structures aimed at mitigating the environmental impact of artificially constructed barriers in river courses, especially dams and weirs.

10.2 River Rehabilitation

10.2.1 Impacts on river health

Impacts on river health can be traced to two broad categories of disturbance that relate to ecohydraulics: disturbance to the river channel and disturbance to the flow regime (hydrology) of the river. There are also numerous impacts on water quality, which are discussed in more detail by King *et al.* (2003).

Channel disturbance

According to King *et al.* (2003), the main sources of physical disturbance to river channels are channelisation, canalisation and instream mining.

The ecological impacts of channelisation include the loss of hydraulic biotopes and a possible decrease in species diversity. Channelisation can occur through various engineering measures, including the following:

- Straightening of the river: Straightening of meanders increases the gradient of the river bed and thus increases velocities and the sediment transport capacity of the river, which can lead to erosion of the channel bed (incision) and a wider and deeper channel. Bank failure can be induced if a critical bank height is reached. A nick point can develop within the straightened reach that can migrate upstream and propagate further erosion and bank failure.
- Creation of embankments: These include dykes and levees that are often used for river straightening and for increasing land available for development on floodplains. Increased energy flows through the narrowed channel tend to cause degradation and sedimentation in downstream reaches and can cause channel incision within the reach.
- Deepening: This is generally done to increase the conveyance of the channel. The deeper sections can cause deposition of sediment, starving reaches downstream of their sediment supply and causing changes in the channel equilibrium.
- Widening: This can lead to a decrease in flow velocities causing deposition of sediment within the widened reach.
- Narrowing: This increases flow velocities and can lead to erosion of the bed and deposition of sediment in reaches downstream.

Canalisation can be defined as lining the channel bed and banks, eliminating bed and bank erosion in the reach, but also eliminating all riparian, marginal and rooted habitats for plants, and eliminating habitat heterogeneity.

Instream mining, generally carried out for construction materials, changes the channel morphology in the same way as deepening and widening.

Hydrological disturbance

According to King *et al.* (2003), the main causes of hydrological disturbance to rivers include construction of dams, abstraction of water and importation of water via inter-basin transfers. Dams cause changes in flow patterns downstream through the attenuating effect of the impoundment and release regimes being different from the natural flow regime to accommodate the different timing requirements of downstream users and hydropower generation. Retention of sediment within the impoundment also reduces sediment loads downstream. Inter-basin transfers of water into a river increase flows, which can cause geomorphological changes to the channel through incision and erosion, channel armouring, bank instability and erosion, loss of pool-riffle sequences or the lowering of high riffles. Diversions of water from a river decrease flows, which can lead to geomorphological changes through sedimentation and channel narrowing.

Land-use changes, such as urbanisation, can also disrupt flow and the supply of sediment to areas downstream. According to Smith-Adao and Scheepers (2007), Beaumont (1981) was able to link instability in the Hout Bay River, Western Cape, to land-use changes in the catchment. Beaumont (1981) reported that the removal of catchment and channel vegetation increased flood peaks which resulted in significant channel erosion and enlargement, with the previously meandering channel becoming straighter. In general, urbanisation and development within a catchment can lead to an initial increase in the supply of sediment during the development phase, resulting in streambed aggradation and over-bank deposition in floodplain areas, followed by a decrease in the supply of sediment and an increase in peak runoff flows after development has been completed, leading to increased bank erosion and channel enlargement as the stream tries to accommodate the increased streamflows (Paul and Meyer, 2001).

The impacts of a disturbed hydrological regime include the first order impacts of changes to flow regime and sediment load, the second order impacts of changes in river morphology and abiotic habitats and the third order impacts of changes in the biotic components of the system (Petts, 1980, 1984, 1988).

10.2.2 Minimising the impact of new engineering works on rivers

For flood alleviation projects, a stream rehabilitation effort is generally directed at reintroducing structures, vegetation, bends, meanders and other variations which create habitat complexity and velocity variation in streams, while the flood alleviation itself is generally aimed at removing obstacles, reducing resistance to flow and increasing water velocities (Brown, 2000). A conflict between the two objectives therefore commonly arises.

Various large structures that can be used to minimise the impact of engineering works on rivers, such as fishways, and outlet structures from dams designed to release the ecological flow requirement are discussed in detail in Section 10.3.

The following principles are recommended for minimising the impacts of new channel engineering works on rivers:

- Provide unlined channels where practical and design them to achieve non-eroding velocities (City of Cape Town Development Service, 2002).
- Maintain the channel plan form (particularly the low flow meandering channel) (Brown, 2000).
- Maximise species diversity through maintenance of habitat diversity by designing uneven river margins, maintaining riffle-run-pool sequences and maintaining substratum (Brown, 2000).
- Incorporate variation of the cross-section shape to maximise the diversity of instream habitats (City of Cape Town Development Service, 2002).
- Design for compound (multi-stage) channels (Brown, 2000).
- Where possible, utilise off-channel (floodplain) areas as flood detention areas (Brown, 2000).
- Ensure bank stability by maintaining a slope of at least 1V:2H, preferably 1V:3H to 1V:4H (Brown, 2000), although others such as the City of Cape Town Development Service recommends 1V:4H to 1V:7H.
- Incorporate a riparian fringe with indigenous vegetation where possible (City of Cape Town Development Service, 2002).
- Where it is not possible to keep channels unlined, use concrete as a last resort. Riprap provides a rough and pervious lining that can provide a diversity of habitats, even though these may not be the kind of natural habitat that occurs locally (City of Cape Town Development Service, 2002).
- Minimise the need for future mechanical intervention (Brown, 2000).

Minimising the impacts of engineering on riverine ecosystems by definition increases the reliance on soft engineering options (Brown, 2000).

10.2.3 Approaches to the rehabilitation of degraded rivers

Depending on the nature of the degrading disturbance, rehabilitation of a river may require rehabilitation of flows (usually through adjustment of release regimes from upstream dams), or rehabilitation of the channel, or both. Watson *et al.* (1999) and King *et al.* (2003) amongst others, recommend similar systematic approaches to rehabilitation projects. The approaches include the following general phases:

1. Initiation – assembling a project team including specialists, problem identification, determining a reference condition and establishment of rehabilitation goals.
2. Planning – prioritisation taking into account the constraints, such as determining the size of the project, the time required and fiscal limits.
3. Analysis – evaluation of alternatives and strategies to reach project goals, a systematic approach to make informed decisions, preliminary design and feasibility.
4. Implementation – detailed engineering design, construction and inspection.
5. Monitoring – establishment of requirements for maintenance and repair of features, and post-project assessment; this provides an essential feedback loop to planning and design of future projects.

Ractliffe and Day (2001a) emphasise the importance of a team approach with specialists from various disciplines being involved. They also caution that within a limited budget, care should be taken not to over-extend the scope of the project, resulting in only part of the suite of rehabilitation measures required for successful execution being undertaken. Watson *et al.* (1999) emphasize that it is important to identify the problems in the river reach and establish the goal of what the rehabilitation is aiming to achieve at the outset of the project as this improves the chances of project success.

King *et al.* (2003) also mention that the natural recovery process of the river can be allowed to run its course instead of a costly rehabilitation program being undertaken. This would be appropriate in cases where no irreversible alterations to the channel have been imposed, no significant urban development has taken place, no regulation of flows is occurring, and the recovery time-scales can be determined and are acceptable.

As river rehabilitation is very much a developing field in South Africa, Ractliffe and Day (2001a) recommend that an assessment of the effectiveness of the rehabilitation project be undertaken at the end of the project and then again some time later – even several years later – once enough time has elapsed for vegetation to establish and the effects of floods on the erosion protection structures to become obvious.

Rehabilitating disturbed channels

Watson *et al.* (1999) provide guidance on the rehabilitation of river channels from an engineering perspective for the USA, although the general principles are applicable anywhere. Schoeman and Quinn (2003) provide a prototype decision support system for the selection of stream bank rehabilitation techniques for South African rivers with banks less than 3 m high. A value and threat rating which are combined to determine a priority score are determined for the river bank at each location to aid in prioritisation of rehabilitation sites. Flow charts are then used to guide the planner through the selection process. The system was tested to the preliminary design stage on the Foxhill Spruit in Pietermaritzburg, KwaZulu-Natal. Russell (2007) provides valuable information for the rehabilitation of wetlands in South Africa and many of the techniques are also applicable to rivers.

Watson *et al.* (1999) state that it is important to keep in mind that a river is a system, and that it is wise to consider the impact of any rehabilitation measures on the rest of the river system through a comprehensive evaluation and analysis. According to Watson *et al.* (1999), it is important during the preliminary design phase to determine whether the river channel is stable through a geomorphic assessment, using standard methods such as the maximum permissible velocity, tractive force and regime theory channel design methods. An initial stable channel design is carried out and evaluated against the proposed rehabilitation goals. If the goals are satisfied by the design then no further work is required and the design can proceed to the detailed design of local stabilisation and habitat enhancement features. However, if the goals are not satisfied due to system instability or a need to modify design parameters to meet project goals, which is usually the case, then an iterative design process is initiated in which design parameters such as channel-forming discharge and stable channel dimensions are re-evaluated and various measures for restoring stability such as grade control, bank stabilisation and planform properties are considered.

Once the design phase is initiated, some background investigations should be conducted into the climate, geology, geography and hydrology of the basin and the relationships and effects of these on the stream. Records of past behaviours should be sought out from nearby gauging stations, historic maps, aerial photographs, historical photographs, botanical records, palaeostage indicators and older residents. A hydrological analysis of the basin should be conducted with an appropriate hydrological modeling program. A detailed field investigation should also be carried out. A preliminary channel design based on stability evaluation should be conducted early in the project planning, to screen out alternative designs that would present serious stability problems and to identify future needs. As planning progresses, successive evaluations with increasing detail may be required to ensure that the final channel design addresses stability problems thoroughly, thus avoiding costly future channel maintenance efforts. Channel design computations are based on a design discharge which can be based on computed hydrological events such as a 10-year storm event or on the channel forming discharge that is responsible for shaping the channel morphology (as discussed in Chapter 8). A field assessment of stable reaches in the area can be conducted to determine the likely stable slope of the river reach to be rehabilitated. Maximum permissible velocities, tractive force design and regime theory channel design can be used. Maximum permissible velocities for channels are given in the Drainage Manual (Rooseboom, 2006) and by Watson *et al.* (1999). Stable channel design can be carried out using the US Army Corps of Engineers program HEC-RAS, which can perform the Copeland, Regime and Tractive Force methods. HEC-RAS can also carry out mobile bed sediment transport analyses and sediment impact analyses for analysis of existing and proposed channels.

According to Ractliffe and Day (2001a), striving to restore the specific historical features of a system to its natural state is not possible in urban areas where rivers are intensely modified by alterations in water chemistry and physical encroachment/manipulation, and may not even be a useful starting point in some cases. Instead, a more realistic yardstick of ‘ecological success’ is the extent to which a project can maximise potential habitat diversity and quality and/or rehabilitate or create particular habitats that are threatened in an urban setting such as floodplain corridors. The inclusion of meanders, varied bank slopes and off-channel and in-channel wetland areas can improve habitat (City of Cape Town Development Service, 2002).

Rehabilitating flows

James and Thoms (submitted) state that different channel forms require different discharges to produce the same hydraulic conditions. This is because the necessary translation of discharge into local hydraulic habitat conditions is site-specific, as the same discharge will produce different local hydraulic conditions in different channel morphologies, whether these are associated with different locations in a river or with changed conditions at a particular location. This should be borne in mind in river rehabilitation projects in order to maximise habitat availability.

Rehabilitation of previous alien invaded areas

There is potential to use hydraulic modeling methods to predict water levels and velocities for river cross-sections after future clearing of riparian alien vegetation, to aid in determining the possible indigenous plant communities that may have grown there prior to invasion. This information could be used for re-vegetation programmes that may be initiated to rehabilitate the area. Reinecke *et al.* (2007) investigated various predictors and used the distance from summer low-flow water's edge and the height from the edge of the water to indicate where each indigenous plant assemblage would probably occur in various Western Cape rivers. According to Reinecke *et al.* (2007), the use of height and distance from water was useful for predicting what species would have grown at heavily invaded or cleared sites, but less so for sites with floodplain development; it was not effective for Afromontane Forest sites because of their steep narrow valley shapes. King (pers. comm.) has suggested that hydraulic modeling may provide better predictors such as flow velocities at various points along the cross-section and water surface levels for various discharges. Successful hydraulic modeling would depend on informed estimates of roughness values for the future indigenous plant communities along the river banks and in the channel (some guidance for estimating the resistance effect of bank vegetation is given in Chapter 7).

Restoring a river invaded by exotic invasive vegetation may be complicated due to changes in the channel caused by the exotic vegetation. For example, Versfeld (1995) described how the invasion of Black Wattle (*Acacia mearnsii*) caused severe bank erosion which in turn led to channel widening along the Disa River in Cape Town, and Smith-Adao and Scheepers (2007) hypothesised that channel morphology changes such as bed and bank erosion, channel migration and narrowing, in-channel deposition and bar formation observed on a reach of the Lourens River in the Western Cape were due in part to alien vegetation invasion.

10.2.4 Bank and bed erosion protection materials and approaches

The protection of river banks and beds from erosion can be undertaken using various methods, including so-called bio-engineering methods which typically combine biological and engineering concepts and more traditional hard engineering approaches.

It should be kept in mind that no single stabilisation technique is applicable to all situations (Watson *et al.*, 1999) and that soil bio-engineering systems are not suitable for every project (King *et al.*, 2003). The attainment of long-term stability of bio-engineering systems depends on the successful establishment of dense vegetation with sound root systems and selecting the appropriate plant species is thus important to the success of bio-engineering systems.

Re-vegetation

Rehabilitation may be possible through appropriate re-vegetation without structural aids. Suitable species may already be growing on site and may be left to re-colonise the area naturally and unaided. For wetlands, active re-vegetation (the manual planting of vegetation) is important if there are risks involved in waiting for natural recruitment to occur (Sieben *et al.* 2007). It is important to assess such risks. The rehabilitation plan should specify the benefits as well as the risks of not embarking on active re-vegetation as opposed to simply facilitating natural re-colonisation. Sieben *et al.* (2007) also recommend that mono-specific planting should be avoided for wetland areas as a greater diversity of species leads to a greater chance of the system surviving the stresses of changing characteristics. Sieben *et al.* (2007) present a decision tree for selecting appropriate vegetation for banks of streams.

Active re-vegetation is normally most successful when the natural patterns of distribution of the native plant species in the aquatic and riparian areas are utilised. The assemblage of species found in each zone is adapted to surviving the inundation and exposure patterns pertaining to the zone. Before re-vegetation is performed a thorough analysis of the microclimate, soils, site conditions, and vegetation at the site, amongst other things, should be completed (Gray and Leiser, 1982). Relevant erosion processes occurring at the site must be identified, and plant species need to be matched with the identified erosion areas (Shaw, 1999; Rutherfurd *et al.*, 2000). Planting must take place in the right season and an appropriate planting technique must be used. It is important to note that re-vegetation normally begins with pioneer species that easily take root from cuttings or start from seeds and create the environment for the succession of other species. An irrigation system should be used until the plants are established (Riley, 1998). The site must be monitored and managed to ensure that it is reasonably stable for at least one growing season after planting, thereby encouraging the plants to establish themselves (Gary and Leiser, 1982; Gore, 1985).

Rooseboom (2006) (in the Drainage Manual) recommends erosion protection design velocities for various combinations of indigenous and exotic grass species, soil types and mean annual rainfalls. The first consideration for a design is the ability of the vegetation to establish itself, followed by the selection of a design velocity based on recommended design tables and figures. Rooseboom (2006) recommends that the permissible velocity for vegetated soils should not exceed the allowable velocity for unprotected soils by more than 30%. Russell (2007) also provides recommended velocities for various soil types and grass covers. Brown (2000) states that little or no work has been done into determining velocities that various plants can withstand, but Hoag (1993) suggests that in the USA velocities should not exceed

- 1 m/s for herbaceous species alone
- 1-1.5 m/s for woody and herbaceous species mix, and
- 1.5-2.5 m/s for woody species alone

For velocities exceeding 2.5 m/s, engineered river banks usually require additional stabilisation.

Brush mattresses

A brush mattress (see Figure 10-1) is a mulch of hardwood cuttings placed on the face of a bank and interwoven or fastened down with jute wire or cord held in place by stakes. Heavy, unrooted cuttings are normally planted before or after the mattress is placed. Gray and Leiser (1982) point out that consideration needs to be given to things like seasonal planting requirements and the difficulties of planting through the mattress. Brush mattresses provide direct protection from erosion, encourage sediment trapping and allow roots to grow, thereby strengthening the soil. Further bank protection is realised when a vegetation cover develops and reduces over-bank velocities. The banks need to be sloped according to the terrain and soil texture, and a slope of 1V:2H or flatter should be used as a general guideline, as plant establishment on steep gradients is difficult (Bowie, 1982; Miller, 1996), although Sieben *et al.* (2007) maintain that steeper slopes can be accommodated with wire and pegs. Sieben *et al.* (2007) state that unanchored brush mattresses are only suitable for low velocity areas, while anchored brush mattresses can withstand intermediate velocities. Sieben *et al.* (2007) provide in-depth guidelines for brush mattresses.

Figure 10-1 Photograph of pegged brush mattress (African Gabions, 2004, in Sieben *et al.*, 2007)

Hedges and vegetative bundles

Vegetative bundles (see Figure 10-2) are cigar-shaped bundles of live cuttings approximately 2 m long that are tied and placed in trenches, staked, partially covered with soil and laid along contours of banks (Sieben *et al.*, 2007). By reducing flow velocities, they provide protection along the contours of steep cuts and embankments where the use of vegetation will be effective. They involve the use of both vegetative and structural material. Plant bundles or tree trunks are typically fixed in furrows above installed pegs along the slope. According to Rooseboom (2006), they are generally effective on slopes of 1V:2H or flatter but can in some instances be used on slopes steeper than 1V:1.5H. Aesthetic appeal is enhanced by the development of vegetative cover. The procedure for installing hedges is outlined in the Drainage Manual (Rooseboom, 2006) and by Sieben *et al.* (2007).

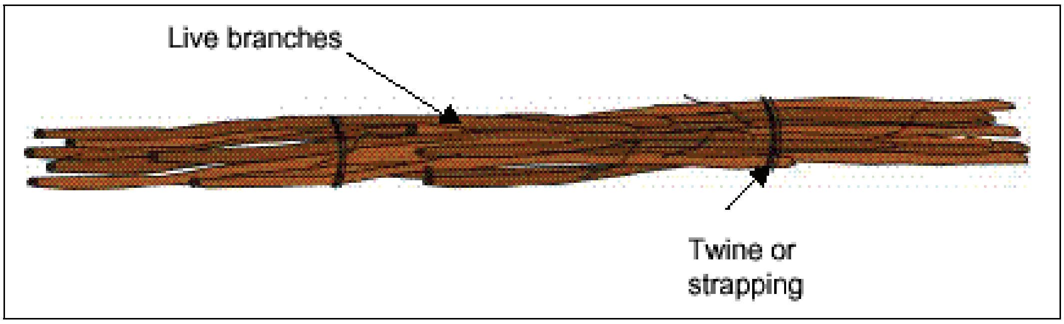


Figure 10-2 Vegetative bundle tied every 250 mm apart (Sieben *et al.*, 2007)

Geotextile fabrics

Geotextile fabrics are woven netting made from synthetic or natural fibres. Examples of natural fibres are jute, sisal, coir and cotton fibres and examples of synthetic fibres are polymer and nylon. In general, natural fibres are preferred because they tend to be biodegradable and are less likely to cause harm to organisms when washed out. Coir fabrics are a popular choice owing to their high tensile strengths, their ability to withstand high flow velocities, and the fact that they do not rot easily. Depending on the material, geotextile fabrics can be used as temporary or permanent measures (Luger, 1998; Riley, 1998). As temporary measures, their function is to provide protection for a sufficient length of time to allow a dense vegetation cover to develop. It is estimated that the lifetime of biodegradable geotextiles is between five to seven years. Hoitsma (1999) is of the opinion that this estimate is optimistic and considers two to four years as more realistic. As permanent or long-term measures, geotextiles remain long after vegetation cover has developed and continue to provide protection in the event that the vegetation cover is damaged.

Figure 10-3 Fibre mats covering compacted soil berms in a seepage wetland that had previously been drained (Sieben *et al.*, 2007)

Fabric-encapsulated soil lifts

Fabric-encapsulated soil lifts, also known as geogrids, are normally designed to provide protection against shear stresses before vegetation is established (Miller, 1996; Fogg and Wells, 1998; Hoitsma, 1999). They are coarsely textured gravel-like sediments or soils wrapped around by or encapsulated within two layers of biodegradable geotextile coir fabric (King *et al*., 2003). They may be used to strengthen and protect the upper slope or mid-section of the bank, and are normally between 0.9 to 2.3 m wide and 0.3 to 0.7 m high. The geogrids are placed perpendicular to the bank at slopes from 1:1 to 3:1. The inner fabric prevents fine sediment from escaping through the coarse outer layer and comprises a non-woven (see Figure 10-3) mat of coconut fibres held together with polypropylene thread mesh. The outer fabric is a heavy weight coir fabric of twisted coconut fibres woven into a strong mesh, which provides structural integrity to the lift and hence the bank. Planting deep root cuttings between the geogrids and placing grass and forb seeds through slits beneath the coir fabric layers on the face and top of each of them can ensure long-term stabilisation. This results in good colonization by riparian plants before the fabric disintegrates.

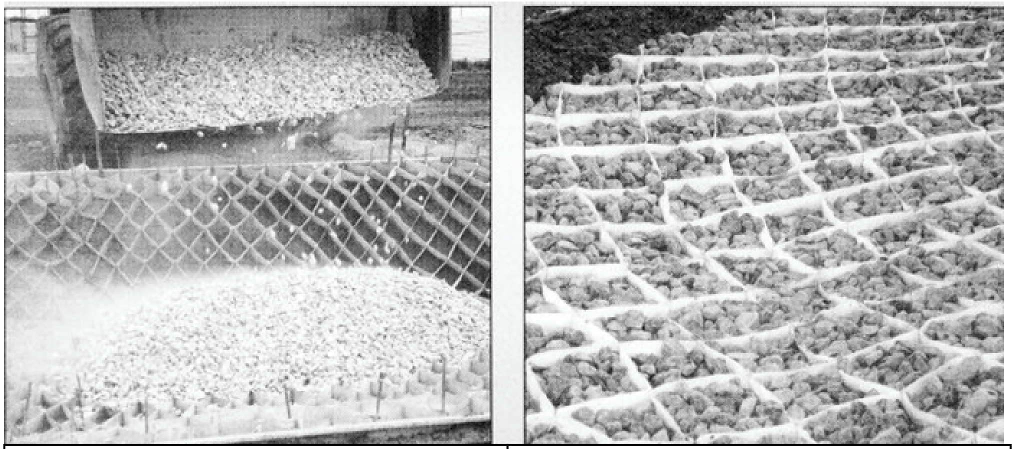
Geocells

Geocells such as Grasscrete, Dymex, Gobimat or Hyson cells, are cellular confinement membranes, filled with topsoil and planted with vegetation or alternatively filled by pouring concrete or soil cement *in situ* into plastic formers (see Figure 10-4). Made of synthetic material, the cells are installed within the banks and seeds are planted on the exposed surfaces. They are normally covered with geotextiles and, upon the development of a vegetation cover, provide a high resistance to erosion with the intricate web of cells and interlocking plant roots.

While the use of synthetic materials results in relatively expensive structures (Hoitsma, 1999), it has the advantages of light weight, ease of installation and suitability for both labour intensive and mechanical filling (Russell, 2007). However, according to Luger (1998), geocells offer few environmental benefits besides being preferable to solid concrete.

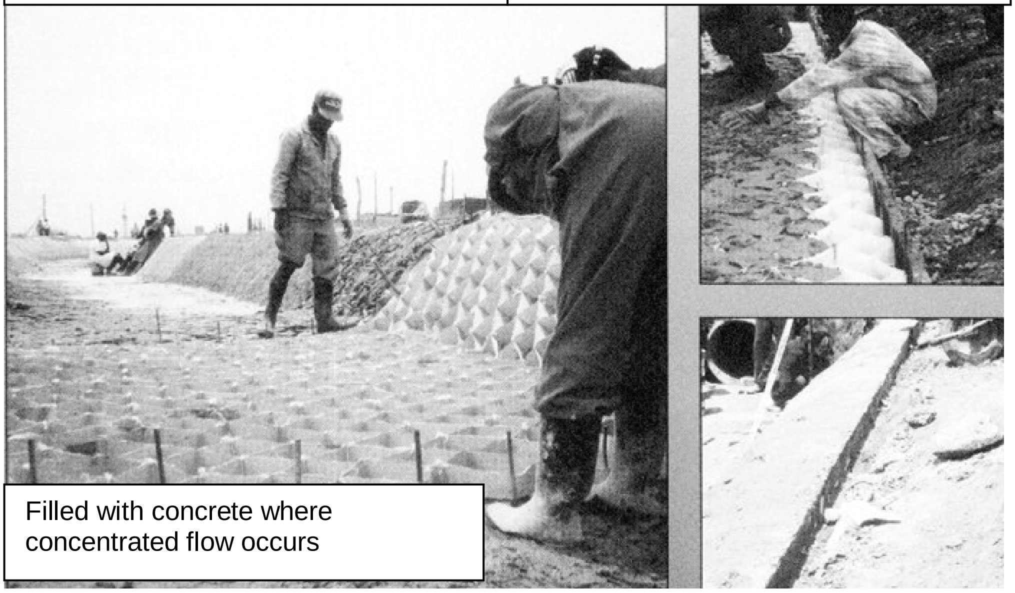
Used motor vehicle tyres

Russell (2007) suggests the use of old motor vehicle tyres for the erosion protection of gully bank walls in wetlands (see Figure 10-5). The channel banks should be re-graded to a gradient of 1V:3H or flatter and a topsoil layer spread over the bank. Russell (2007) recommends that a design velocity of 2 m/s can be used, but where velocities will exceed 3-4 m/s, serious damage can be caused to the lining. The tyres are either bolted or wired together using galvanised material and iron rods can be driven through the mattress into the soil profile every 3-5 m for added stability. Soil is placed and firmly compacted into the holes in and around the tyres and vegetation is established. It should be borne in mind though that tyres are inflammable and should not be placed in areas where veld fires occur frequently.



Filled with soil or gravel to stabilize slopes

Filled with loose rock to stabilize slopes



Filled with concrete where concentrated flow occurs

Figure 10-4 Various applications of geocells (Russell, 2007)

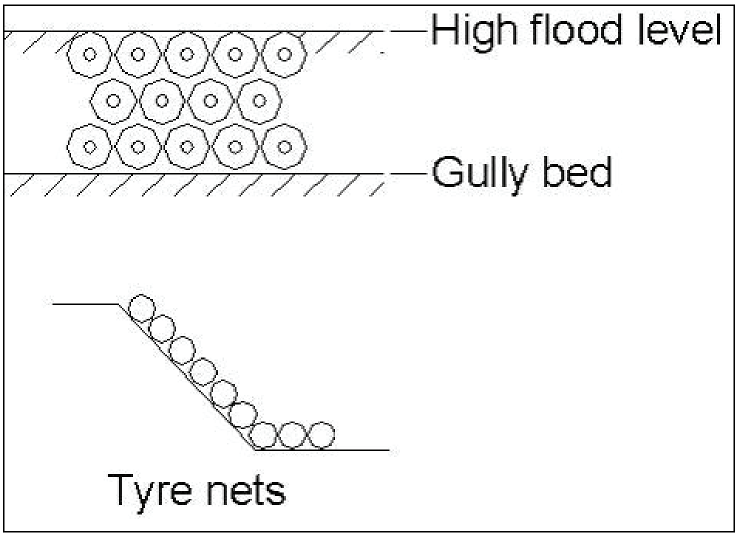


Figure 10-5 The installation of tyre nets: Typical frontal view/cross section (after Russell, 2007)

Interlocking concrete blocks

Patented interlocking concrete blocks such as Grassblock, Armourflex, Terraforce, Terrafix, Loffelstein and Grinaker Waterloffel are cell structures mostly used for the protection of evenly graded slopes, particularly channel bends (see Figure 10-6). They contain soil which can be vegetated to improve their aesthetic appeal. Design criteria for prefabricated paving blocks are presented in the Drainage Manual by Rooseboom (2006).

The use of concrete blocks depends on the availability of a good foundation. The drainage system also needs to be adequate to avoid severe pressure gradients between the front and the back of the walls (Precast, 1992). They are often laid on filter layers such as geotextiles or graded granular material to prevent soil loss, but this may restrict root penetration. For an adequate plant cover to develop, there must be a sufficient depth of soil within and below the blocks.

Guidance on the hydraulic design of prefabricated concrete blocks of all shapes is available in the Drainage Manual (Rooseboom, 2006).

According to Ractliffe and Day (2001a), grassblocks do provide slope stabilization, but their purported ability for establishment of vegetation in the small holes in the blocks was not apparent in their assessment except in one case where Winblocks were used which have much larger planting holes. Therefore interlocking concrete blocks with larger planting holes should be selected, and it may be appropriate to create steps in areas that are steep.

Figure 10-6 Terrafix blocks used for erosion protection of a channel bed (photo courtesy of Terraforce)

Riprap

Riprap protection is the most commonly used erosion protection option because of the availability of material, ease of construction and relatively low costs depending on location (Jansen van Vuuren *et al*., 2006). Riprap provides crevices and rough surfaces where sediment can accumulate, plants can grow, and animals can shelter (Luger, 1998). To ensure maximum interlocking of particles, it is recommended that the riprap is well graded with the individual stones having a length to width ratio of 1:3 or less. The materials used should also be hardy and not weather easily or be prone to chemical wear (Jansen van Vuuren *et al.*, 2006). Guidance on the hydraulic design of riprap is available in the Drainage Manual (Jansen van Vuuren *et al.*, 2006; Rooseboom, 2006).

Gabions and stone mattresses

Gabions and stone mattresses are normally used in cases where the stones available are too small to function as individual units. The sizes of the stones used in relation to the mesh must be considered carefully to prevent loss of material (Rooseboom, 2006). The creation of gabion and stone mattresses is labour intensive, which may be an advantage where local job creation is an important aspect of a project. They do not require a solid rock foundation and can absorb some settlement, are relatively simple to construct, can be built in wet environments and do not require a drained surround for stability (Russell, 2007). A disadvantage is that their costs of installation and maintenance are high compared to riprap. Also, they are less flexible and therefore are more prone to catastrophic failure than riprap (Jansen van Vuuren *et al.*, 2006).

Stone mattresses should be laid to protect banks that are no steeper than 1V:2H and preferably 1V:1.5H (Russell, 2007). Cut-off walls, suitable filter material as per the manufacturer's prescription or linings should be provided where necessary (Rooseboom, 2006).

Gabions can be constructed as a wall for bank protection (Figure 10-7) although Rooseboom (2006) recommends that gabions and stone mattresses should only be considered for small streams with no vertical stability problems. Guidance on the hydraulic design of gabions and stone mattresses is available in the Drainage Manual (Jansen van Vuuren *et al.*, 2006; Rooseboom, 2006).

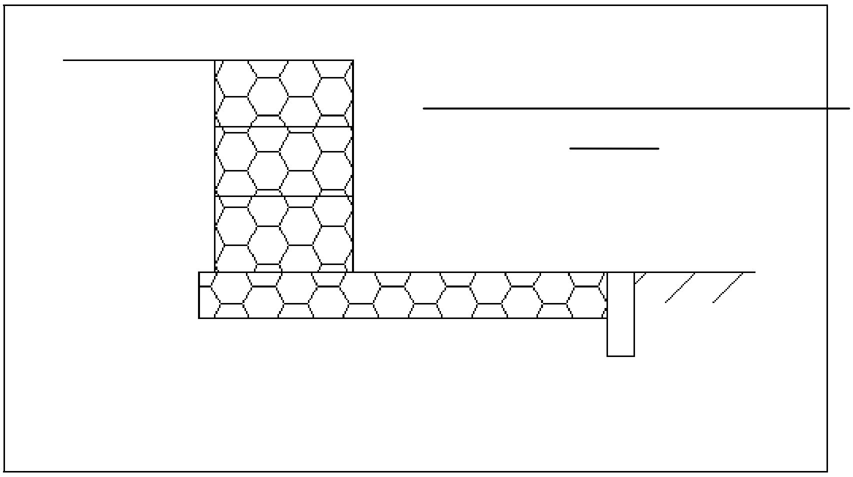


Figure 10-7 Protecting stream bank with a wall of gabion baskets on a mattress: Typical cross section (Russell, 2007)

According to Russell (2007) gabions and stone mattresses should only be regarded as medium term solutions due to corrosion of the wires, especially where water flowing over and through the structures is acidic, even with galavanised wires. The corrosivity of the water should be checked and if the water is found to be corrosive then either PVC coated wires should be used or the use of gabions should be rejected in favour of other options (Russell, 2007). Rusting of the wires can be counteracted through ensuring well established vegetation growth on the structure, with the roots of the plants and the sediment that has been trapped often able to take over the function of holding the structure together (Sieben *et al.*, 2007). However, if any steps imposed by a gabion structure on the slope of the land are more than about 0.5-1.0 m high, then the roots may lack the strength to prevent the structure collapsing. Thus Russell (2007) recommends that gabion weir structures be stepped on their downstream side, with vertical steps not exceeding 0.5 m. The potential for theft of wires (Russell, 2007) and damage to the PVC coating of the wires from veld fires (Rooseboom, 2006) should also be taken into account.

Ractliffe and Day (2001a) recommend that in order to promote colonisation of gabions by vegetation, the void spaces between the rocks in the gabion should be filled with soil. This is difficult to do once the gabions have been completely filled. Thus they recommend that after every 0.5 m of the gabion basket has been filled with rock, soil should be added. Arranging the gabions so that there is a space between steps where topsoil can be placed to sufficient depth for planting can be successful. Widening gabion-lined channels to the full extent of available space spreads flows, which is desirable, and the application of topsoil outside of the low flow part of the channel and/or insertion of soil-filled, bidem-lined pockets in the gabions, followed by vegetation, provides better aquatic habitat. Planting directly into crevices in gabions on stepped channel banks that are not close to the channel bottom is unlikely to be successful for any but the most hardy of plants (usually weeds) due to lack of moisture. In addition and where appropriate, rhizomes of appropriate deep, strong rooting plants such as *Phragmites australis* and Palmiet can also be inserted into the voids. Russell (2007) recommends that soil only be placed between the rocks where velocities will be less than 2 m/s. For stone mattresses and gabions Russell (2007) recommends that the design velocity should not exceed 3 m/s, to reduce the risk of rocks being washed out of the mattresses in the future when the wires have corroded.

Geotextiles and geoliners are probably necessary behind weirs, and keying of the structure into the banks and bed needs to be done with care (Russell, 2007). According to Ractliffe and Day (2001a), gabion weirs should be tied in to the adjacent bank or floodplain to allow for planting of their surfaces, preferably so that marginal habitat can be created along these areas.

10.2.5 Structures for erosion protection and increasing habitat availability

Habitat diversity is provided through a variety of physical conditions such as flow depth, flow velocity, extent of inundation and the time distribution of these (James, 1995). In a natural river these are provided through variations in alignment such as meandering, an undulating bed profile with deep pools and rapid flow over riffles, irregular banks and vegetation. Traditional practices such as channelisation, canalisation and clearance of vegetation typically result in change or loss of these habitats. Feeding and spawning habitats are key to the rehabilitation of rivers, and there is therefore the need to re-establish or re-create altered or destroyed habitats. The following three primary approaches to promoting variety in the riverbeds are presented by Harper *et al.* (1999):

- Promoting erosion and deposition to recreate diversity of substrata and physical conditions.
- Replacing lost substrata through the construction of artificial riffles and pools. This method is suitable in the middle and lower reaches of rivers.
- The introduction of artificial or natural material like quarry rejects, boulders, gravel and woody debris.

Coarse materials such as boulders alter the flow pattern and create hydraulic diversity leading to improved aeration of the water. Associated developments such as scour holes and downstream bar formation provide cover and substrata for animals as well as additional habitats for rearing fish. Rehabilitated rivers or rivers that are modified to increase their conveyance should include as many of the natural features as possible and where appropriate, features such as islands, shallow-water berms, pools and riffles, shallow bays, stone weirs, meanders and bends.

Woody debris also provides hydraulic diversity. Woody patches are particularly important in deep and mobile bed rivers, where they provide a hard surface for organisms and are a source of food and refuge for a variety of flora and fauna. Re-introduction of woody debris must be considered where it has been lost or removed as it plays a vital role in the health of rivers. It can be introduced as cut logs, trunks with attached roots, or entire trees (Rutherfurd *et al.*, 2000). Wood does not last as long as rocks but may be generally cheaper and more readily available (Brookes *et al.*, 1996).

Unfortunately there is a price to pay for trying to maintain or reinstate habitat diversity as all the features that enhance ecological functioning of a river channel also detract from its hydraulic efficiency, because they all increase flow resistance (James, 1995). It is more difficult to evaluate the resistance effects of a channel that includes these features compared to a channel that is uniform (James, 1995).

The structures and channel designs given in this section can be used in river rehabilitation to reduce erosion and to create habitat heterogeneity in a river reach.

Groynes

Groynes are typically constructed of rocks, boulders, gabions and reno mattresses, logs and concrete or metal sheet piling (see Figure 10-8). They generally protrude at about right angles from the river bank to guide flow away from the river bank under threat and reduce velocities in the area of the bank, and may be placed upstream or downstream of the area to be protected. They provide the added benefit of habitat creation by promoting scour and deposition in other areas of the channel. Design considerations for groynes are presented in the Drainage Manual (Jansen van Vuuren *et al.*, 2006). Various configurations or arrangements can be used along the bank and the spacing between groynes is normally a function of the length of intrusion, the mean flow depth and the channel roughness. Special considerations should be made in narrow rivers to determine if the use of groynes on one bank will initiate erosion on the other. It is recommended for most cases that a model study be performed due to the complex nature of the interaction between the factors that affect the layouts and spacing (Jansen van Vuuren *et al.*, 2006).

Figure 10-8 A system of gabion river groynes protecting a stream bank (Russell, 2007)

Retards

Retards are low permeable structures made from materials like piles, wire mesh, cables, tree cuttings, steel and timber. They are typically arranged in a fence-like manner extending into the channel, and provide protection on the outer bank and bed of a bend. They are also used for channel narrowing and alignment stabilization. They function by reducing secondary currents and flow velocities behind the structure (Julien, 2002). Sediment deposition as a result of the reduced velocities provides niche substrata for plants to colonize. The vegetation that eventually is established, will improve stability and enhance the riparian appearance of the banks (Henderson, 1986).

Jetties or jacks

Jetty or jack fields comprise longitudinal and lateral rows of jacks usually fastened together with cable (Figure 10.9). They increase the roughness along the bank reducing flow velocities and protecting it against erosion. Jetty fields trap debris and promote deposition, and are particularly effective in streams with high debris and sediment loads. Suitable vegetation is needed to stabilise the sediment (Russell, 2007). The spacing between the lateral rows is dependent on the debris and sediment loads in the stream. Jacks are normally made from wood, metal or concrete, and are essentially basic triangular frames fixed together to form stable units (Henderson, 1986; Rutherfurd *et al.*, 2000; Julien, 2002). According to Russell (2007) jacks have been used with great success in the Karoo using concrete poles.

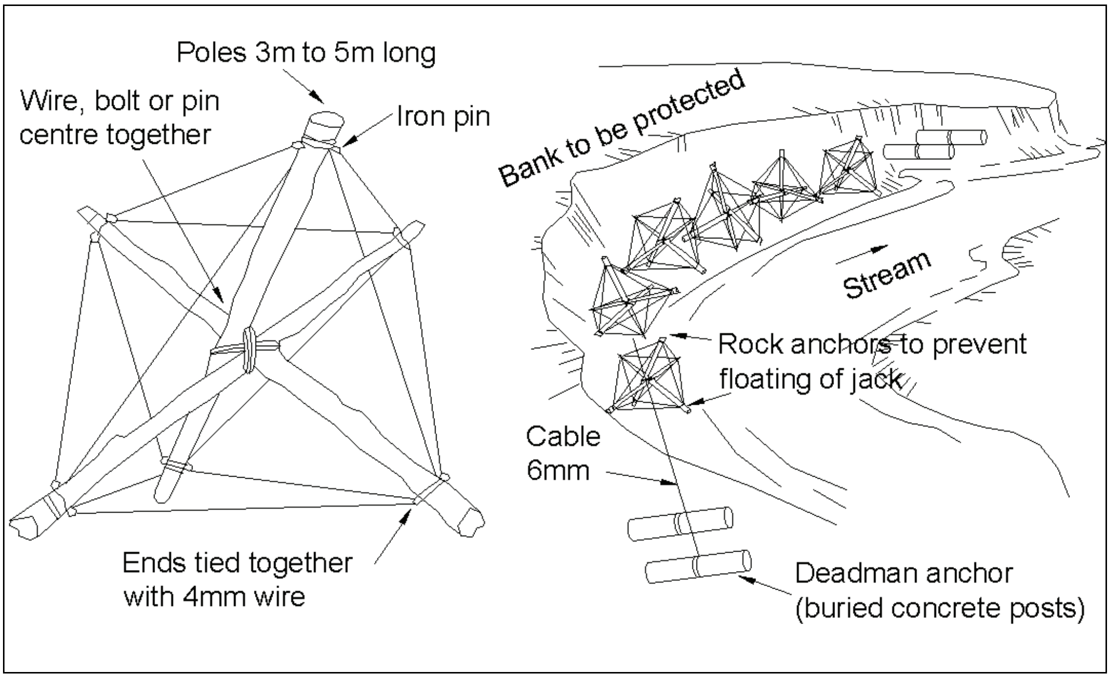


Figure 10-9 Use of river jacks to stabilise bank erosion (Russell, 2007)

Lunkers

Lunkers are large wooden or plastic crib-like structures placed at the toe of a bank to provide cover and shelter for fish (Figure 10.10). They also double as a protection measure and can be used to stabilise the water line and upper bank. Lunkers have both ends and the stream side open. The riverbank is first cut back to create a trench in which the lunker is installed. Riprap and soil are then placed behind and on top of the lunker so that the bank is graded to its edge (Rooseboom, 1994). The bank can be seeded and, with a little ingenuity, the stream health can be enhanced even further.

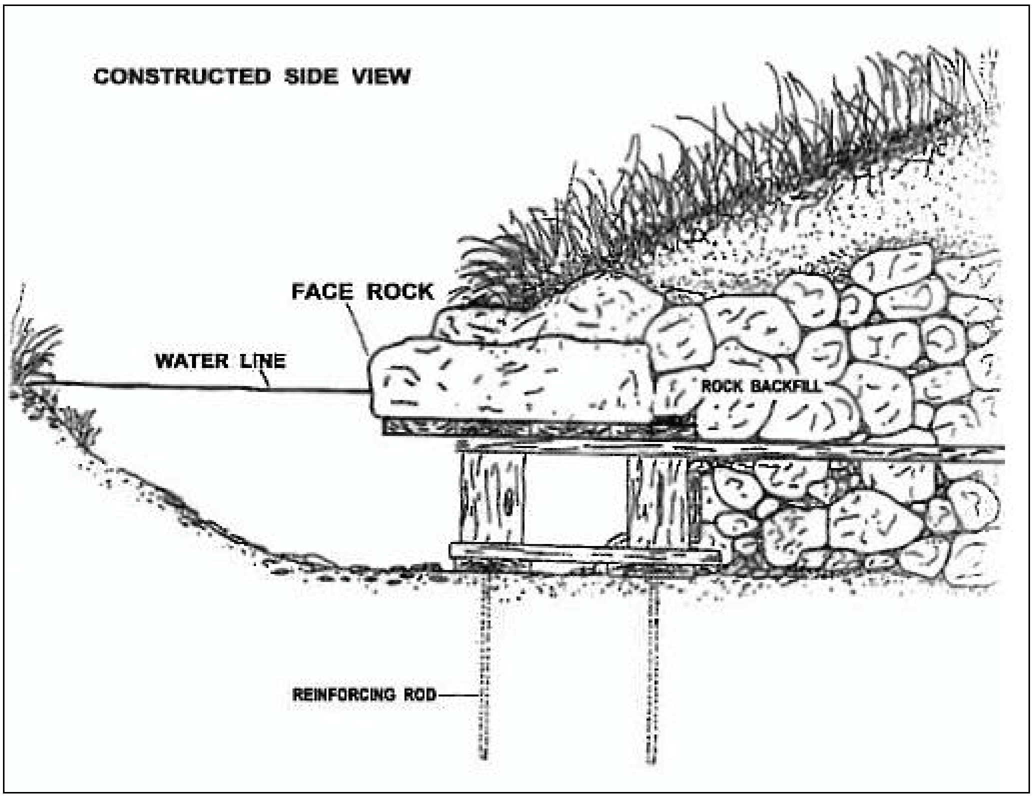


Figure 10-10 Cross section through a lunker and river bank (Vernon County, 2009)

Submerged vanes

Vanes function by directing flow away from the bank. They can be used for bank protection, deepening of channels, creating scour pools, promoting deposition, and reinstating meanders. They are normally designed to operate under bankfull conditions (Stewardson *et al.*, 1999), and can be constructed from erosion resistant material such as rock (Julien, 2002). Their effectiveness is influenced by their location, length, spacing and orientation.

In general, partial width structures have the benefit of realigning the channel, removing silt from spawning gravel, controlling the water temperature, providing specific locations with flow, increasing flow velocities, creating narrower channels, creating deeper low flow channels, creating scour pools and downstream bars, and formatting bars for colonisation by riparian vegetation (Gore, 1985; Brookes *et al.* 1996; Rutherfurd *et al.*, 2000).

Artificial riffles

Habitats can be enhanced through the creation of artificial riffles. This can either be by recreating a natural riffle formation or creating a permanent riffle structure (Rutherfurd *et al.*, 2000). Natural riffle formations are created from imported materials with size distributions close to those of the existing bed material.

Creation of permanent riffle structures involves the introduction of rocks that are larger than the existing bed material, such as natural or quarried riprap boulders. These rocks are tightly packed and, with the presence of oversized rocks, provide a variety of habitat conditions. Riffle creation exercises must recognize the importance of connectivity along the channel and should not result in the prevention of migration of aquatic organisms (Rutherfurd *et al.* 2000). Permanent riffle structures should be designed in accordance with sound hydraulic design principles, such as those presented in the Drainage Manual (Rooseboom, 2006).

Regular spacing must be avoided as a general guideline for the design of artificial riffles. They should be spaced at intervals between three to ten times the bankfull width (Brookes, 1995). Also, they must be located in straight reaches to facilitate meandering alignments. According to Brookes (1995), riffle creation is usually unsuccessful in ephemeral rivers, reaches with steep slopes, and in locations where there are severe sediment-transport problems or bank instability.

Drop structures

Implementation of bank stabilization measures without proper consideration of the stability of the bed can result in costly maintenance problems and failure of structures (Watson *et al.*, 1999). Some sort of grade control or drop structure may be needed to ensure that a stable bed slope is maintained.

Drop structures are low structures that extend across the width of a channel. Examples include weirs, check dams and sills. They typically control the longitudinal profile of the river, and can enhance habitat diversity through the creation of pools and riffles. Construction materials vary between logs, rocks, boulders, gabions, rock mattresses, metals and concrete (Brookes *et al.*, 1996; Shields *et al.*, 1995, 1997).

Attributes of drop structures include the following:

- Pool creation both upstream (damming effect) and downstream (scouring effect).
- Bar creation and riffle-like features downstream of scour pools.
- Increase in flow variability (Luger, 1998).
- Entrapment of gravels and fines.
- Re-oxygenation of water.
- Development of a stable substratum.
- Provision of food to benthic organisms by reducing flow velocities and allowing organic debris to settle.
- Checking upstream migration of headcuts and stabilisation of the bed level.

Concrete is the strongest and most durable material for constructing drop structures but is generally more expensive than stone masonry (Russell, 2007), however the use of these materials is most appropriate where there is a sound bedrock foundation. Gabions are not suited to sites where fishways will be required (Russell, 2007) but are more suitable for poorer founding conditions where downstream erosion with gabion mattresses may also be required. Stone masonry (see Figure 10-11) is a good construction material in South Africa because it does not require shuttering like concrete, is long-lasting, does not contain wires that corrode like gabions, is attractive and tends to be cheaper than gabions and concrete. Concrete buttress weirs (see Figure 10-12) are cheaper than any of the above-mentioned mass structural options and arch weirs (see Figure 10-13) are good for wide gullies where transport costs of material are expensive (Russell, 2007). Timber weirs and rock packs are not recommended by Russell (2007) due to the large number of failures observed.

Figure 10-11 Rock masonry weir in a wetland environment (Russell, 2007)

Figure 10-12 A U-shaped concrete buttress weir constructed on a gabion structure encased in concrete in a wetland environment (Russell, 2007)

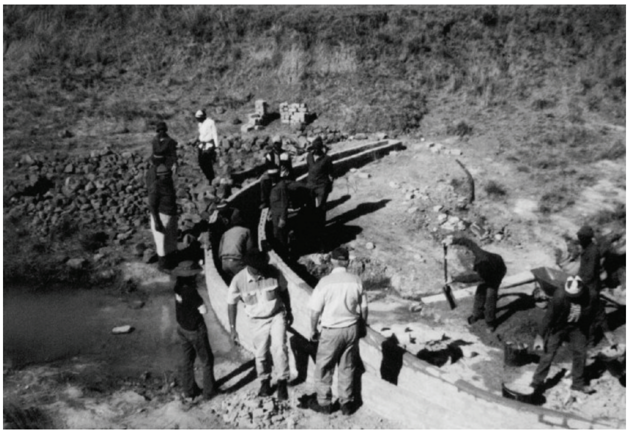


Figure 10-13 Building an arch weir, double walls of concrete bricks with concrete fill in-between. Planned for raising once the sediment has reached the spillway level (Russell, 2007)

Russell (2007) recommends that a minimum number of grade control structures should be incorporated in wetland rehabilitation efforts in the interests of economy, and this should be borne in mind for river rehabilitation projects as well, where appropriate. Nielsen (1996) recommends that drop structures should be placed at different angles and at irregular distances where possible, to offer a greater diversity of flow strengths and patterns.

The hydraulic design of drop structures (see Figure 10-15) for stability against erosion and to provide localised energy dissipation is well established and is presented in the Drainage Manual (Rooseboom 2006) and by Russell (2007) (see Figure 10-14). According to Russell (2007), the design of drop structures should include adequate erosion protection at the toe to prevent a scour hole from eroding upstream under the structure. Shoulder walls can be incorporated into the design both upstream and downstream of the structure to prevent bank erosion (Russell, 2007). Drop structures should also be keyed far in to the bank and river bed to ensure that the drainage path through the soil around the structure is sufficiently long to prevent erosion of fines. The spillway of the structure should be designed to have high enough velocities to scour sediment that would otherwise block the spillway, yet should be as wide as possible to reduce concentration of flow and hence erosion on the downstream side of the structure, taking into account potential erosion of banks downstream. Sufficient freeboard should be available for the parts of the structure that are above the spillway where this is appropriate. Values for recommended freeboards are given by Russell (2007). Russell (2007) recommends that instream structures such as drop structures should be designed to withstand a 1:10 year flood for small structures in small catchments of less than 50 ha, a 1:20 year flood for moderately sized structures in catchments of 50 to 500 ha, and a 1:20 to 1:50 year flood for large structures unless dam safety regulations require otherwise. The choice of design flood also takes into account the trade-off between capital cost and maintenance. It is also important to check the structure for resistance to sliding and overturning. Attention to the design of the foundation for the structure is also very important.

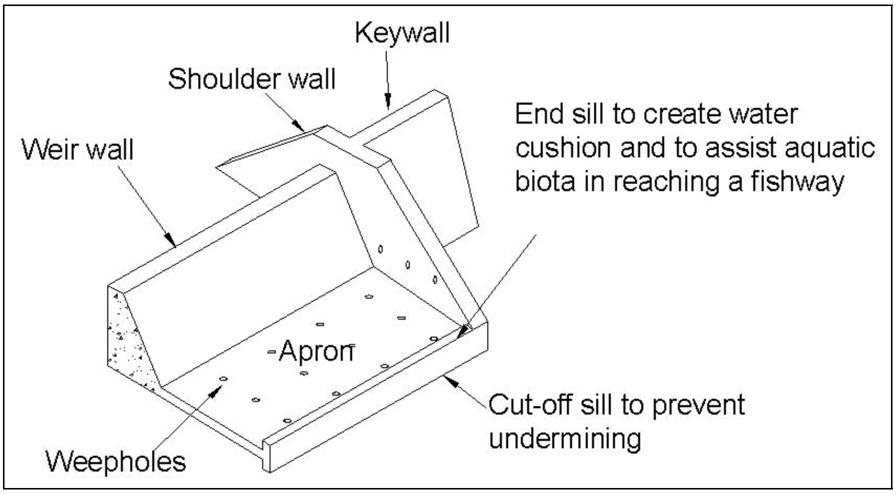


Figure 10-14 Components of a weir drop structure (after Russell, 2007)

Drop structures can have a major impact on natural stream function (City of Cape Town Development Service, 2002) and a major concern is the break in longitudinal connectivity along the channel – it may be necessary to include a fishway in the design. The design of fishways for South African rivers is discussed later in this chapter. The City of Cape Town Development Service (2002) recommend that drop structures should be limited in height to < 1 m and/or tied into the channel sides to allow for longitudinal migration of fish; the specific requirements of fish should be established where pertinent to the environment.

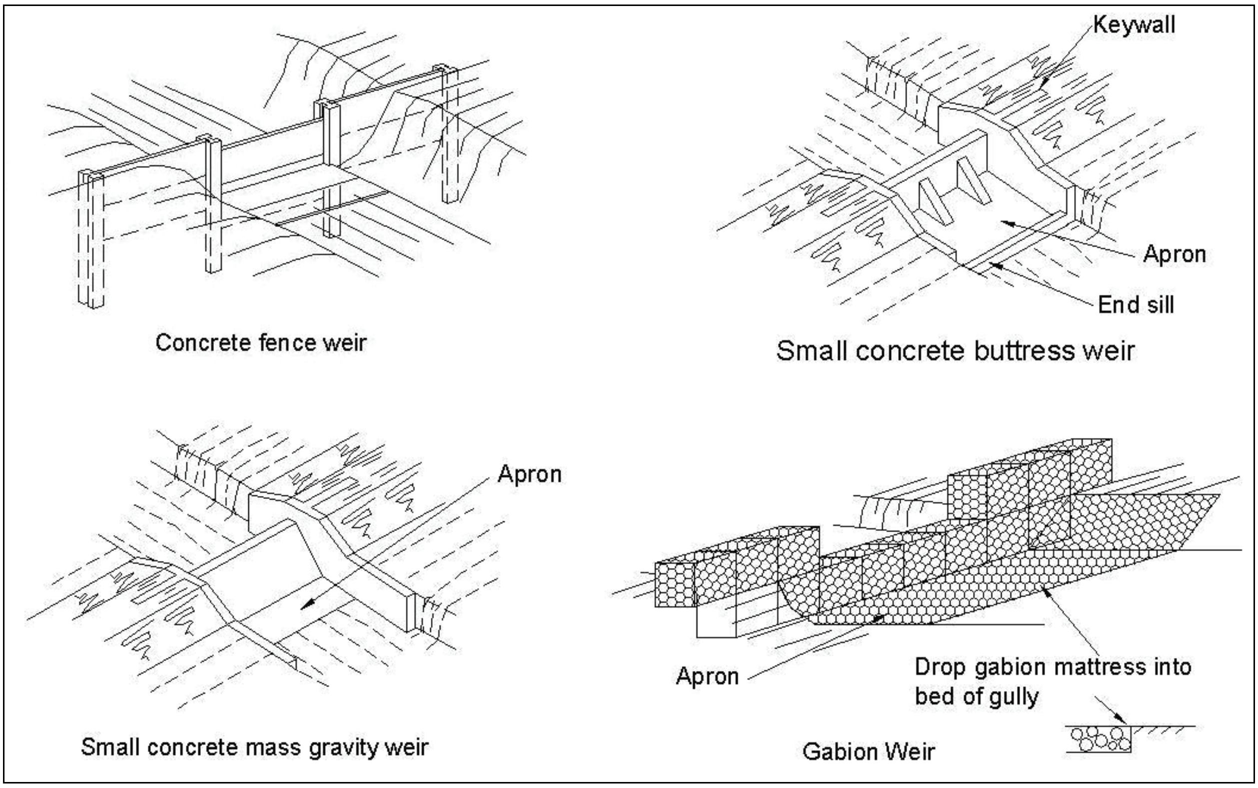


Figure 10-15 Small drop structures that can be used in small eroding gullies generally less than 1 m deep (after Russell, 2007)

Multi-stage or compound channels

James (1995) provides guidance on the design of compound channels, where a floodplain is cut into the side of the channel to increase conveyance capacity, but the existing channel is left intact to maximise the diversity of habitats. This is a compromise between increasing flood conveyance capacity while trying to maintain some habitat diversity in the river. A compound channel which contains flow within the channel and also on the floodplains has additional effective resistance due to momentum transfer through the shear zones between channel and floodplain. A one-dimensional hydraulic modeling software package may not take into account the momentum transfer between channel and floodplain and therefore two-dimensional modeling methods, or the simpler hand-calculation methods of Ackers (1991, 1993) for a straight channel and floodplain, or James and Wark (1992) for meandering compound channels may be preferable. These methods are described in Chapter 7.

Vertical and horizontal undulations that mimic the variable contours of natural habitats are important, not only in terms of the aesthetic appeal desired of ‘green’ open spaces, but because they produce diversity in local habitat conditions (e.g. of aspect, wettedness and degree of shelter from wind) that are mirrored in plant and animal diversity. A compound channel should include large scale meanders of the high flow channel, low-flow channel meanders within the high-flow channel or floodplain, variations in the channel width to create variety in depth and velocity, irregularity in plan of the channel margin, irregularity of the channel profile and varying gradients of the stream side slopes both along the course of the river and up the bank (Ractliffe and Day, 2001a).

Brown (2000) recommends that in the design of multi-stage channels, it is better to only disturb one side of the channel and leave the other in its natural state. Engineering works should shape the bank in steps which are graded to hold the different floodlines or the recognized vegetation zones.

Reconnecting the floodplain with the river

Floodplains can be reconnected with rivers through restoration of flows in remnant channels in the floodplain, through the creation of secondary channels that connect the river with the floodplain or to remove embankments that cut the floodplain off from the river (King *et al.*, 2003). An attempt to reconnect the Hout Bay River with its floodplain wetland is described later in this chapter.

Reinstating meanders

Reinstating meanders is popular in northern hemisphere countries and examples include the Rivers Cole and Skern in the United Kingdom described by The River Restoration Centre (2002). According to King *et al.* (2003), in most cases the objective is to restore sinuosity and connections to the floodplain. If at all possible, meanders should be aligned along the old meandering courses of rivers, using guidance from old maps and other information. Alternatively, the meander wavelength is generally about 8 to 10 times the width of the stream channel. Relationships from other natural meandering rivers can also be developed if possible. Meander bend spacing is normally very variable and this should be taken into account in the design. According to King *et al.* (2003) four approaches to the design of meanders have been summarised in the literature: the carbon copy method where the meanders follow the exact original alignment of the river; the use of empirical relationships developed for specific regions; the natural approach where the stream is allowed to find its own path although this can take a long time to reach a stable channel form; and the systems approach which includes an analysis of undisturbed meanders, the geomorphology of the disturbed area and consideration of the interaction between the stream and the surrounding areas. Reinstating meanders is usually not done in isolation and goes hand in hand with bank reshaping, bank stabilisation and re-vegetation practices (King *et al.*, 2003).

Reshaping of banks

Banks can be reshaped to prevent bank collapse and increase habitat availability. Brown (2000) recommends improving bank stability by cutting banks back to flatter slopes, preferably 1V:3H to 1V:4H, although others such as the City of Cape Town Development Service recommend 1V:4H to 1V:7H. Bank slopes should have varying gradients both along the course of the river and up the bank to increase habitat availability.

10.2.6 The role of hydraulic design and modeling in river rehabilitation

There is considerable literature on the design of grass-lined channels, riprap revetments, gabions, stone mattresses, geocells, grass block type protection measures and the use of such measures for groynes and drop structures, such as the guidelines contained in the Drainage Manual (Rooseboom, 2006; Jansen van Vuuren *et al.*, 2006). However for many of the other approaches described above, sound judgement based on the effectiveness of the existing natural vegetation and other measures against erosion may provide the best approach. Judgement should preferably be supplemented by the hydraulic determination of flow velocities and depths for the range of flow conditions in the river, so that similar measures that have proved to be appropriate in similar local circumstances can be utilised.

10.2.7 River rehabilitation case studies

Various South African river rehabilitation projects that were found in the literature are discussed briefly in this section. Many more river rehabilitation projects have been undertaken in South Africa and an investigation into the success of rehabilitation projects in the area of a proposed rehabilitation project should be undertaken to improve understanding of best approaches for that area. Ractliffe and Day (2001b) reviewed various river and wetland rehabilitation projects that were undertaken in Cape Town and their review gives more detail on a few of these projects.

Brookwood stream flood management strategy, Noordhoek, Cape Town, 1998 (Ractliffe and Day, 2001b)

The main objective of this project was flood management. The Brookwood channel is an artificial watercourse that was upgraded to find an environmentally acceptable engineering solution to manage water flow in the sub-catchment.

The channel was designed with a trapezoidal cross section with riprap lining placed on biddim extending across the base and 0.5 m up the channel sides. The channel banks were revegetated through grassing of the upper banks, using *Stenotaphrum secundatum* (buffalo grass) in two reaches and *Pennisetum clandestinum* (kikuyu) in the third reach. A short section of concrete-lined low-flow channel within a riprap-lined larger channel was also constructed. The channel is perfectly straight except for four sharp bends, where earth stilling ponds were constructed. A pre-treatment pond was also constructed at the outflow from the river reach for water-quality purposes.

During the site visit, Ractliffe and Day (2001b) noted that plants had taken root in sediment that had accumulated on the base of the channel with the greatest diversity of plant species being present where the stream width was greatest and channel gradient less steep. However, the riprap-lined channel sides remained bare. Plant diversity was noted to have increased since March 2000, suggesting that a natural process of vegetation within the channel was occurring steadily. Ractliffe and Day (2001b) state that in relation to the environmental ‘advantages’ of the project, it certainly had provided for instream riverine habitat, albeit not by design and not of a type that was natural to this system. They noted that the deposition of sediment on the channel bottom and subsequent growth of vegetation could lead to a reduction in capacity of the channel to pass high flows with time.

Ractliffe and Day (2001b) suggested that the ecological impact of the channel would have been greatly improved by:

- inclusion of a wider channel to reduce flow velocities,
- inclusion of shallower and more heterogeneous side-slopes through variation of the position of the toe and the gradient of the slopes, and
- planting of riparian vegetation and a wider corridor for the river channel that would have allowed the development of a zone of riparian fringing vegetation capable of providing habitat and shelter for wetland and other animals moving along the channel.

Similarly, expropriation of land for the channel took the most convenient straight lines along property boundaries – expropriation of a more imaginative (but bureaucratically more difficult) curving alignment would have provided scope for meandering of the channel.

Diep River upgrading, Constantia, Cape Town, 1996 to 1999 (Ractliffe and Day, 2001b)

The main objectives of this project were rehabilitation of riverine habitat and erosion control through bank and bed stabilisation.

The river had been severely impacted through urbanisation in the catchment, channelisation and associated bank erosion and collapse, modification of flood flows through the construction of an in-stream detention pond, extensive loss of natural riverine and riparian habitat, invasion by alien vegetation, sedimentation of downstream areas and abstraction of water from the river.

In an attempt to rehabilitate the river, alien vegetation was removed, low gabion weirs were installed at intervals along the river to re-grade the channel, limited replanting of indigenous riparian vegetation was conducted and banks were re-graded and shaped in places. The gabion weirs were sited according to a surveyed long-section of the river, taking into account local factors such as gradients of banks, susceptibility to erosion and flow velocity. The channel was rerouted in certain areas to an irregular path in plan, including backwaters and sheltered seasonally-inundated areas. One of the weirs that was constructed during the wet season was washed away during construction and had to be reconstructed. Maintenance on the channel has included manual removal of sediment from the channel and deposition of the removed sediment in side channels.

Ractliffe and Day (2001b) state that overall, the project resulted in a number of very positive changes in the riverine ecosystem. The use of gabion weirs was found to be an effective measure to reduce energy in the channel and thus erosion of the banks, while also having the positive effect of allowing the build-up of sediment and the creation of more diverse riverine habitat. Sedimentation upstream of the weirs resulted in the creation of sandbars, backwater habitats and seasonally inundated shallow water margins, all important habitats in the area that would have been characteristic of the river under natural circumstances. They found that the removal of alien trees that had shaded the river aided the growth of indigenous vegetation within the channel that improved the quality of habitats. A section of riprap was added upstream of one of the weirs as backfill and created a small riffle which, although probably not representative of indigenous habitat, did add some habitat diversity. The use of logs to prevent erosion along paths and sections of the upper river banks was largely ineffectual – flow was found to be concentrated at irregularities in the logs and gully erosion was exacerbated.

Ractliffe and Day (2001b) found that where the gabion weirs had been less effective, this was due mainly to inadequate maintenance rather than to poor design. One of the weirs was bypassed by the river and their suggestion was that bank terracing and the installation of adequate erosion protection around the weir using stone mattresses should have been carried out. They also stated that cost-cutting that excludes sufficient erosion protection around these types of structures can lead to failure of the structure and therefore, if budgets are limited, it is better to undertake sound rehabilitation of smaller areas only.

It was found that the areas of the river exhibiting the greatest benefit from the rehabilitation activities and which appeared to be sustainable were where an integrated approach was undertaken, including reduction in energy in the stream through the construction of weirs, bank stabilisation, clearing of alien invasive vegetation and re-vegetation with appropriate indigenous vegetation. Where only weirs were constructed, bank collapse remained a problem, for example.

Hout Bay River upgrading, Phase 1, Hout Bay, Cape Town, 2000 (Ractliffe and Day, 2001b)

The main objectives of this project were to improve public amenity and rehabilitation of riverine habitat.

One of the aims of this project was to restore connectivity between the river channel and the floodplains near the estuary which had been cut off due to the historical construction of levees. This was done by excavating two gaps in the levees which would become active during high flow periods. Unfortunately the two gaps were not excavated to design levels according to Ractliffe and Day, but were excavated by the contractor by eye only and these levels proved to be too high, thus the attempt at connecting channel and floodplain failed.

It was also intended to re-grade some of the river banks to create improved marginal riverine habitat, to restore access to and from the river by small animals and to reduce erosion by improving plant cover. However, Ractliffe and Day (2001b) reported that the banks were not graded to shallow enough slopes due to construction taking place during a period of high river stages, and as a result, the slopes were unstable with widespread undercutting, slumping and collapse of the river banks occurring during the winter of 2001. A retrospective recommendation was that flatter slope gradients of 1V:5H or 1V:6H would have improved habitat quality and diversity.

Wooden revetments were used to stabilise some of the banks against scour. Terraforce blocks were also installed to stabilise the dune river banks which were planted with *Cynodon dactylon* grass sods. Unfortunately extensive erosion was noted behind the revetments, due partly to impinging flow from the Baviaanskloof River which entered the main stream opposite this section, nearly at right angles to the main stream, and erosion caused by high flows in the narrowly channelised Hout Bay River itself.

Ractliffe and Day (2001b) suggested that erosion of the river banks may have been reduced through routing of flood flows through the floodplain on the west bank. The aims of the project did not include flooding and river capacity and it was noted that these issues should have been addressed by the project.

Keysers River restructuring, Tokai, Cape Town, 1998 (Ractliffe and Day, 2001b)

The main objectives of this project were flood management and rehabilitation of riverine habitat.

Before implementation of the project, the channel was a deep earth channel with vertical and eroding banks separated from the wetlands that comprised the floodplain. The conceptual plan included rehabilitating the river as an unlined river that was landscaped and planted with appropriate plant species. Alterations were made to the channel to increase its capacity to accommodate the 1:50 year flood through the excavation of a slightly elevated floodplain on one bank only, establishment of a more natural river corridor irregular in plan and with improved ecological functioning, removal of alien vegetation and revegetation with indigenous plants.

The original levee on the left bank of the river was removed over a length of 300 m, creating a floodplain some 15 to 25 m wide and about 200 mm above the channel. The floodplain was sloped at a gradient of 1V:4H towards the channel. The profile of the macro channel was ‘irregularised’ by an excavator under the supervision of the environmental planners. The channel was made to be irregular in plan, cross-section and longitudinal profile. The channel was tied into a concrete-lined canal section at its downstream end through the use of stepped gabions on the channel banks. Stormwater drainage channels from adjacent urban areas were extended through the floodplain channel to the edge of the low flow channel and lined with reno mattresses. The floodplain channel was planted up or seeded with *Cynodon dactylon* grass.

It was noted that dredging of the channel is undertaken from time to time, which also removes the instream vegetation that would characterise this sort of stream. No erosion within the floodplain was evident during the site visit by Ractliffe and Day. It was also noted that the low flow channel remained straight and uniform in width and depth, although the adjacent floodplain channel was irregular except for the bank of the floodplain channel which remained uniform and straight. Ractliffe and Day (2001b) consider that it would have been preferable to design the channel with a varying cross-section and plan form. It was found that various wetland species of plants had spontaneously colonised the area along the margin of the low flow channel providing marginal habitat, although these had not been specifically included in the planting plan. There was improved connectivity between the river and the wetland and the well vegetated banks provided cover for small animals. Invasion by kikuyu grass was noted to be a problem and it was suggested that low-maintenance plants should be chosen.

Overall it was found that the project had been successful in improving the flood capacity of the channel while at the same time retaining the natural soft-bottomed characteristic of the river type. The project was also successful in rehabilitating a large marginal wetland with good potential to support a diversity of flora and fauna.

Kuils River bank rehabilitation, downstream of Stellenbosch Arterial road, Cape Town, 1998 to 1999 (Ractliffe and Day, 2001b)

The objectives of this project were rehabilitation of riparian habitat, erosion prevention and stormwater treatment.

Illegal infilling of a wetland and the illegal excavation of a new river channel were to be rehabilitated in this project. This would be through reshaping of the new channel and increasing its depth to accommodate dry season flows including bank slopes, bed elevation and the removal of berms to allow inundation of the wetland during the rainy season; connection between the channel and the former channel-like pond section to the west of the channel and the raising of this ponded area to create a riparian wetland area; and re-establishment of a reedbed and bankside vegetation to provide habitat and to prevent erosion of the banks.

The removal of the berm was done by hand labour, the previously infilled land was removed and lowered by 0.5 m and protrusions into the main channel were cut away. Unfortunately the removal of the berms was not completed. The deeper sections of an old aquaculture dam were filled to create a wetland platform. Steep banks further downstream were re-graded to shallower slopes. Grassblocks, with alternate blocks removed to increase space for planting, were installed as erosion protection along a bank of the river adjacent to a road in one section. Various local plants were used in the re-vegetation exercise. Unfortunately planting took place during June, the high flow season, and many plants were washed away. The planting was haphazard and for example no plants were found in the section protected by grassblocks on the site visit by Ractliffe and Day.

Ractliffe and Day visited the site three years after completion of the project and noted that there was no serious erosion of banks evident, that the varied channel margin provided the potential for varied river edge and riparian habitat and that the grading of the infilled area was successful in achieving appropriate levels of seasonal flow into the wetland. The failure not to completely remove the berms was noted as a missed opportunity to increase connectivity between the river channel and the adjacent wetland. It was also noted that the lack of a maintenance period after construction where weeding of alien invasive plants should have taken place, had led to invasion of the area by various aliens. Water quality tests indicated that the swales and wetland areas had a positive effect on various water quality variables that were tested in water flowing into the reach and downstream of the reach.

Langevlei Canal environmental education facility, Retreat, Cape Town, 2000 (Ractliffe and Day, 2001b)

The main objectives of this project were ecological upgrading and the creation of an educational facility in an under-utilised public space that was close to a number of schools.

The river would probably have been a wetland-type river with an ill-defined meandering or braided sand-bed channel. The river had been extensively modified to be a flat bottomed concrete canal. A shortage of funds meant that the improvement of ecological functioning was an unlikely outcome.

A 60 m section of canal wall on one bank was removed and a sloping amphitheatre was excavated to create a backwater or wetland habitat and a natural looking stream bank. The backwater was 7 m wide at its widest point and the gradient of the bank was 1V:5H. Terrafix grass blocks were specified for the side slopes at each end of the feature to tie in with the concrete canal walls and for erosion protection of the banks. Winblocks, which have larger holes than Terrafix, were specified for the base of the wetland portion to enable plant establishment. The Winblocks were installed 300 mm below the level of the base of the canal to allow inundation throughout the year. Three 600 mm diameter concrete ring planters were installed within the concrete canal base. Two 100 mm high weirs were constructed at the upstream and downstream limits of construction to provide for aeration and ponding of water within the channel. The Terrafix blocks were planted with *Stenotaphrum secundatum* (buffalo grass). Planting of the wetland section was undertaken in June, during the high flow season, and the planted vegetation in the wetland portion was almost immediately scoured away. Plants were also removed during cleaning of the canal for maintenance purposes. However despite these problems, Ractliffe and Day (2001b) noted that the water feature considerably exceeded its expected ecological benefits and the wetland exhibited greater plant diversity and zonation than was initially envisaged, including deep water, shallow water, backwater shallows and wetland margin areas all allowing growth of different and mainly indigenous plant species. Frogs, crabs, insects and fish were all observed at the site. The Terrafix blocks further up the slope that were dry, were bare and the buffalo grass had not been successful here. It was concluded that Winblocks were a better choice for planting because of their larger planting spaces. An alternative would have been for only every second Terrafix block to be installed, leaving larger spaces for planting. The weirs were thought to be unnecessary and could be omitted from future similar projects.

Moddergat River improvement scheme, Macassar, Cape Town, 2000 to 2001 (Ractliffe and Day, 2001b)

The objectives of this project were flood management, the creation of a public amenity and the rehabilitation of riverine habitat as a secondary objective.

A section of the Moddergat River was upgraded to improve its flood conveyance without canalisation, and the upgrade was devised by a multi-disciplinary team. Prior to implementation of the project, the river was highly modified from its natural condition, which is thought to have been a wide, braided wetland-associated system with meanders through a soft substrate. The project design included a high-flow flood channel and a low-flow channel lined with loose river boulders with allowance for colonisation by dense reed beds, installation of five gabion weir drop structures, and safeguarding against deep erosion particularly in the early stages of the project before establishment of vegetation using a high-density polyethylene mesh along the bank zone between the high- and low-flow channels. The low-flow channel was designed with side slopes of 1V:3H to 1V:4H and with the allowance for deposition of sediment on the river bed. The high-flow channel was situated about 0.5 m above the low-flow channel base with a flattened earth bed; stepped gabions were used in areas where space was limited. The gabion weirs included scour protecting stone mattresses and were built across the entire channel in steep sections. Meanders were incorporated into the river but their number and breadth were limited by space constraints. The stone mattresses were filled with topsoil. The base and banks of the high-flow channel were grassed with *Cynodon dactylon*. It was found that the edging of the low-flow channel restricted the growth of dense reeds to the low-flow channel, but where the edging of boulders was absent reeds were invading the high-flow channel as well, reducing the flood capacity. The boulder lining of the low-flow channel was found to create good quality instream riffle habitat, even if this was not a natural habitat for this area. The addition of the boulder lining to the low-flow channel prevented it from meandering and forming bars and backwaters. The gabions were found to have remained sterile structures accommodating only occasional weedy plant species. The gabions did not add much value to the riverine habitat, but served an important function in dissipating energy in the channel. Although grassing of the high-flow channel had greatly increased the amenity value of the channel, it had not succeeded in creating a high quality river habitat and Ractliffe and Day (2001b) suggested that increasing the width of the planted fringe of the low flow channel would have improved habitat dramatically. It was also suggested that irregular construction of the high- and low-flow channels could have increased habitat diversity and the inclusion of some wetland areas would have been positive.

Silvermine Lower River flood control scheme: Phase 1, Fish Hoek, Cape Town, 1999 to 2000 (Ractliffe and Day, 2001b)

The objectives of this project were flood management and rehabilitation of wetland habitat.

The lower reaches of the original Silvermine River would historically have been unconfined with the channel migrating across a wide coastal plain but in more recent times development had confined the river to a narrow channel. The flood conveyance capacity of the river was increased through excavation of material from the river corridor that was used to infill areas to levels above the 1:50 year flood level. The channel slope was decreased to 1:1000 through the construction of two gabion weir drop structures. The high flow portion of the channel was excavated to a level below the water table to allow for sufficient flood flow capacity which unfortunately clashed with the ecological desire to create seasonal wetlands that would be situated above the water table. It was originally desired to maintain the original river channel as a low-flow channel but due to the depth of excavation required for the high-flow channel to satisfy the required flood conveyance capacity, the low-flow channel was done away with and water was left to flow through the wetland with no defined channel. A deeper section was excavated alongside the original river channel and longitudinal bars were constructed and vegetated with reeds to provide cover for various animals. Unfortunately the requirement to achieve adequate flood flow capacity meant that certain features that would have increased habitat heterogeneity were not included, such as open water, emergent islands and seasonal pans. Variation in the toe position and bank slopes would have provided a more natural looking finish with greater habitat diversity. It was noticed that after heavy rains in 2001, erosion was confined to areas of the second phase that were still under construction.

A river rehabilitation planning pilot trial of the Ihlanza River, East London, 2004 (Uys, 2004b)

Uys (2004b) conducted a river rehabilitation planning trial on the Ihlanza River, which flows through an urban area of East London. The river has been heavily impacted through development of the catchment into an urban area, the construction of a concrete canal in its upper reaches and various culverts in its middle reaches including one underneath a shopping centre located over the stream.

Uys made use of the Australian Stream Rehabilitation Guidelines by Rutherford *et al.* (2000), using steps 1 to 9 of the 12 step process. A detailed assessment of the river was undertaken in terms of its present day geomorphology, vegetation, fish, invertebrates, assets and problems. The following rehabilitation measures were then recommended for each section of the river:

- A detention pond in the upper reaches to reduce peak flood flows and to improve the water quality.
- Clearing, landscaping and stabilisation of the channel and banks in the middle reaches including a compound channel design planted out with indigenous vegetation, clearing of alien invasive vegetation, the creation of semi-permanent riffle/run/pool sequences (that would not be washed away during floods) and the construction of a series of small detention ponds. Terraforce or Loffelstein walls, stepped gabion walls or gab-block revetments were suggested for stabilisation of the river banks.
- Certain parts of the middle reaches would be left essentially as they were, with only minor bank stabilisation measures using gabions and bank reshaping and re-vegetation with indigenous species suggested.
- It was suggested that a part of the middle reaches be re-graded using a series of low gabion or log weirs, including low-gradient rock ramps to allow fish and eels to move upstream.
- It was suggested that for another part of the lower reaches embedded riprap should be used and artificial fish shelters should be installed in pools to increase habitat diversity.

Uys (2004b) provides plan drawings of the entire river showing the locations of all proposed rehabilitation measures and conceptual design drawings of the various rehabilitation options.

Rehabilitation of the morphology of the Hex River, Worcester, Western Cape, 1998 (Basson, 1998)

The objectives of the project were to restore the Hex River to a stable morphology after the impacts of downstream mining of river material had caused a nick point to migrate upstream.

Basson (1998) used a calibrated one-dimensional hydraulic model, which could also model non-cohesive and cohesive bed erosion processes and bed load transport, to simulate morphological changes due to mining activity in the river bed downstream of some bridges across the braided Hex River near Worcester in the Western Cape. The model was used firstly to simulate the long-term equilibrium profile due to the mining of material from the river bed downstream of the bridges. The model was then used to design structures that would return the river bed to a stable morphological state that did not threaten the integrity of the bridges, including stilling basins downstream of the bridges to dissipate energy, bank protection using riprap and the construction of two weirs.

Simulation of the Berg River estuary to predict impacts from the construction of the Berg River Dam, Western Cape, 2006 (Beck and Basson, 2006)

Beck and Basson (2006) simulated the Berg River estuary using Mike 21C, a two-dimensional hydraulic model, to determine inundation areas, depths and velocities in the estuary and compare them between pre- and post-construction conditions of the Berg River Dam.

Simulation of the rehabilitation of flows through the Pongola River floodplain from the Pongolapoort Dam, KwaZulu- Natal, 2006 (Basson et al., 2006)

The Pongolapoort Dam, completed in 1973, has significantly modified the flow regime through the 150 km Pongola River floodplain downstream of the dam, through the reduction in the frequency of floods (Basson *et al.*, 2006). The floodplain contains many off-channel pans, the ecology of which is dependent on inundation from the Pongola River during floods. Artificial flood releases have generally been made in October and February of each year, timed mainly for socio-economic reasons (Basson *et al.*, 2006). Basson *et al.* (2006) found that channel widths downstream of the dam had on average decreased by 35% after construction of the dam. Various models had been set up historically, using one-dimensional modeling methods. Basson *et al.* (2006) used a combination of Mike 11 (a one-dimensional hydraulic model) and Mike 21C (a two-dimensional hydraulic model) to model pre-dam conditions, and various scenarios of demands from the dam and flood release scenarios. The model outputs were used to draw maps showing time-series of inundation depths and velocities on the floodplain and to determine hydrographs at various key points after releases from the dam. The results were also used to determine the required size and shape of hydrographs that could be released from the dam to fill the pans on the floodplain. Various initial pan levels were also tested to determine the required releases to fill the pans.

Simulation of various catchment development scenarios and their impact on Oryza-longistaminata (Wild Rice) on the Nyl River Floodplain, Limpopo Province, 2007 (Birkhead et al., 2007; Kleynhans et al., 2007)

Birkhead *et al.* (2007) set up a one-dimensional hydraulic model of the Nyl River floodplain which Kleynhans *et al.* (2007) used to simulate the availability of suitable habitat for the Wild Rice that grows on the floodplain for various upstream catchment development scenarios. It was possible to simulate the availability of suitable habitat for the Wild Rice using known inundation depth, duration, frequency and timing requirements of the Wild Rice. The simulations quantified the sensitivity of the Wild Rice habitat to upstream developments.

Ash River rehabilitation, Free State, 1999 to 2003 (VelaVKE, 2008)

After construction of the Lesotho Highlands Water Project water began to be transferred to Gauteng via the Ash River, a small tributary stream of the Liebenbergsvlei River. Severe erosion and channel incision due to the massively increased flows of up to 40 m^3/s occurred. It was found that the erosion was mainly being caused by the intermittent high flows from the upstream hydro-power station (VelaVKE, 2008). A balancing dam was therefore constructed to smooth the flows in the downstream river reach (VelaVKE, 2008). Various structures were constructed along the reach to dissipate energy including a 20 m high dam, two concrete weirs, a concrete and gabion weir, a rock weir, a small embankment dam with earth spillway, groynes and berms (Figures 10.16 and 10.17) (Vela VKE, 2008).

Figure 10-16 Concrete weir on the Ash River to dissipate energy within the channel (VelaVKE, 2008)

Figure 10-17 Rockfill weir with clay core (after VelaVKE, 2008)

Nuwejaarspruit rehabilitation, Free State, 2003 to 2005 (VelaVKE, 2008)

Inter-basin transfers of water from the Tugela River Basin into the Vaal River Basin via the Sterkfontein Dam are released from the dam into the Nuwejaarspruit. Future large and intermittent releases of up to 70 m^3/s are planned. A hydraulic model of the river was set up to identify areas that would be at risk of erosion and various erosion control structures were designed. These included an energy dissipating weir of unique design to reduce erosion of the channel and floodplain downstream, river training dykes, a rock bar weir and groynes (VelaVKE, 2008).

10.3 Hydraulic structures to mitigate environmental impact

10.3.1 Fishways

Introduction

Many South African rivers contain structures such as dams, storage weirs, diversion weirs, gauging weirs and culverts that form barriers to the movement and migration of aquatic biota. The presence of these barriers is a major factor responsible for the reduction in numbers and ranges of many migratory fish and invertebrate species in South Africa (Bok et al.,2007). Protection against these impacts is provided through legislation in the form of the Environmental Conservation Act (Republic of South Africa, 1989), the National Water Act (Republic of South Africa, 1998a) and the National Environmental Management Act (Republic of South Africa, 1998b) which require appropriate mitigation if any proposed instream structure obstructs the natural migration of indigenous aquatic species. One well-established mitigation measure is the fishway, which Clay (1995) describes as ‘a water passage around or through an obstruction, designed to dissipate the energy in the water in such a manner as to enable fish to ascend without undue stress’.

Despite this situation, only about 57 fishway structures existed in South Africa in 2007, of which approximately 42 were functional to some degree (Bok et al.,2007). Many were not effective in passing fish because they were not designed for South African species or river conditions (Bok et al.,2007). To address local needs, serious research into fishway design in South Africa started in about 2000 (Bok et al.,2004). The guidelines summarised here from Bok *et al.* (2007) are generally concerned more with the upstream movement than the downstream movement of fish, as it is assumed that downstream movement will occur during periods of high flow when structures are spilling. Bok *et al.* (2004) consider it to be extremely important to follow a multi-disciplinary approach in fishway planning and design, requiring the close collaboration of fish biologists, hydraulicians and civil engineers.

Bok *et al.* (2007) provide a set of procedures to be followed by the various role players for assessing the need for a fishway and for its design. Expert judgement and specialist input is required to guide the process successfully.

Fishway types recommended for South Africa

Bok *et al.* (2007) recommend five different fishway designs for South African rivers. These are the natural bypass/rockramp, pre-barrages, vertical slot, notched weir and sloping baffle types.

The preferred choice of fishway (if allowed by the site conditions) is the natural type, created with artificial riffle sections (Figure 10.18). These mimic the hydraulics of natural rapids and can therefore pass a wide variety of species and size classes. They also have the advantages of requiring little maintenance, being largely self-cleaning and aesthetically pleasing, but their feasibility depends on the suitability of the topography and foundation conditions, they require a lot of space due to the low gradients required and they may not operate at low flows due to seepage unless the channel is lined.

Figure 10-18 Bypass rockramp fishway on the Lower Sabie River in KNP under low flow conditions at commissioning in October 2001 showing placement of rocks (Bok *et al.*, 2007)

Pre-barrages consist of low walls downstream of the barrier creating a succession of pools rising to the top of the barrier (Figure 10.19). They can be constructed from natural materials such as large rocks and have the advantage of being largely self-cleaning during high flows, but usually require adaptation after construction to optimise their operation. They require sufficient space and suitable foundation conditions.

Figure 10-19 Pre-barrage on Olifants River (Bok et al.,2007)

Vertical slot fishways consist of a series of pools between weirs with vertical slots which extend to the floor of the fishway (Figure 10.20). They can operate over a wide range of headwater pool levels and can pass relatively large discharges. The twin channel vertical slot fishway can also accommodate a wide range of fish sizes.

Figure 10-20 Large vertical slot fishway at Mauzak, France (Bok et al.,2007)

The notched weir and/or orifice fishway (Figure 10.21) is useful when a small range of headwater pool levels exist, the fishway needs to be functional at very low flows and if the river carries a high debris load, especially in seasonal rivers.

Figure 10-21 **Pool and notched-weir fishway on the Lebombo gauging weir on the Komati River (Bok et al.,2007)**

The sloping baffle fishway (Figure 10.22) can be used when a small range of headwater pool levels exist and when the river carries a high debris load. These fishways are an option if eels or prawns are important target species and a separate eelway or prawnway is not feasible.

Figure 10-22 **Close-up of sloping weir of the Nhlabane pool and weir fishway at low flows, looking up-stream (Bok et al.,2007)**

General design considerations for fishways

A fishway should be designed for the range of flows and the headwater and tailwater levels that normally occur at the time of year when the target species undertake their migrations (Bok et al.,2004). The dimensions of the fishway should accommodate both the smallest and largest fish that are expected to use it, and the flow velocities should not exceed the swimming speed of the weakest swimming migrant.

In certain cases only creeping or climbing species such as eels and prawns may be present in the river and in these cases suitable wetted perimeters or sloping splash zones can be included in the barrier design, and no actual fishway is necessary.

The position of the fishway entrance at the downstream side is extremely important. Fish generally swim in or close to the main flow in the river and tend to swim as far upstream as possible, accumulating at the most upstream point below the barrier, normally near the river bank. The fishway should be sited as close to the barrier as possible and on the bank (to aid smaller fish which may be slower swimmers), otherwise the fish may not be able to find the entrance to the fishway. On-site observations and local knowledge should be used where possible. A minimum depth downstream of the structure is important (low flows should be taken into account if relevant) and ideally there should be a pool at the downstream entrance to the fishway for the fish to wait for suitable conditions to negotiate the fishway. A minimum flow rate is also required through the fishway to ensure that fish are attracted to the fishway.

The fishway exit (the upstream end) should be located a distance upstream of the barrier in an area of low water velocity to ensure that tired fish are not swept downstream over the structure. The invert level of the exit should be lower than the barrier spillway to ensure the fishway operates at low flows.

Auxiliary and attraction water can be used to increase the number of fish that are attracted to the fishway. Auxiliary water is additional water that is provided within the fishway to increase the water velocity and flow at the fishway entrance; it is usually added to the downstream most pool of the fishway from a pipe or channel separate from the rest of the fishway. Attraction water is external to the fishway but is close to the entrance to attract fish to the entrance area of the fishway. Designs can be a slightly lower section of the weir close to the fishway entrance or releases can be made from the structure as attraction water. Attraction water is particularly important in wide rivers and should in general be in the same general flow direction as the fishway flow.

Sedimentation of pools and blockages during floods in the fishway can be a problem and the design should take this into account. Regular maintenance may also be required.

Further reading

The report Guidelines for the Planning, Design and Operation of Fishways in South Africa (Bok et al.,2007) provides a good starting point for the design of fishways in South Africa

Larinier *et al.* (2002) and FAO/DVWK (2002), although not South African publications, give the basic principles of fishway design and present many examples of fishway layout and placement at barriers.

10.3.2 Outlet structures designed to release the Ecological Reserve

Due to the requirements of the National Water Act (Republic of South Africa, 1998a) most dams designed and constructed in the future in South Africa will have to be able to release the Ecological Reserve. This has a major influence on the design and capacity of the dam's outlet works. Examples of two South African dams where this provision has been met are described in the following sections:

Injaka Dam

The Injaka Dam was constructed in the late 1990s to augment supply of water to users in the Bushbuckridge area of Mpumalanga and Limpopo Province and to maintain the perenniality of the Sabie River downstream into the Kruger National Park and Mozambique (DWAF, 1994). The dam was designed with a multi-level intake leading to a low-flow outlet to augment low-flows to the Sabie River and therefore contains an outlet structure designed to release an environmental release, even if it cannot release high-flow requirements. The multi-level intake structure, which can abstract water at four different levels within the dam, is designed so that water with the desired water quality, including temperature, can be released to the river downstream. The environmental releases were planned to be based on observed flows at a gauging weir located upstream of the dam in a relatively undisturbed catchment. According to DWAF (1994), the impact of the dam on the river reach immediately downstream of the dam would be negative, but further downstream where low-flows had been reduced to unacceptably low levels for the environment there was projected to be a positive impact on the riverine ecosystem.

Berg River Dam

The Berg River Dam (Figure 10.22) was designed to enable high- and low-flow releases for the Ecological Reserve and is the first dam in South Africa to fulfil these requirements in terms of the National Water Act (Republic of South Africa, 1998a).

The high flow release capacity from the Berg River Dam is 200 m^3/s (TCTA, 2006), which is a large release capability compared to the hydrology of the site. For example, the 1:100 year peak inflow for the dam is 580 m^3/s and the Recommended Design Flood (1:200 year routed flood peak) for the dam spillway is 305 m^3/s (TCTA, 2006). The dam includes a 63 m high intake tower (TCTA, undated) with two wells: a wet and a dry well. The wet well is used for high flow releases through the bottom outlet conduit via a hydraulic radial gate to control the flow and with a capacity of 200 m^3/s. The dry well has a capacity of 0.3 m^3/s to 12 m^3/s (Rossouw and Grobler, 2008) and serves a dual purpose: it is used for water supply and for low flow releases. The wet well contains inlets at 3 levels and the dry well contains inlets at 5 levels to enable water to be drawn from various levels within the reservoir that are at the desired temperature, which should be as similar as possible to that of the natural inflows. The high flow releases will be made as soon as possible after the inflows to the dam have peaked so as to coincide as closely as possible with the natural hydrographs. Hydraulic model studies were undertaken to optimise the design of the wet well (TCTA, 2006).

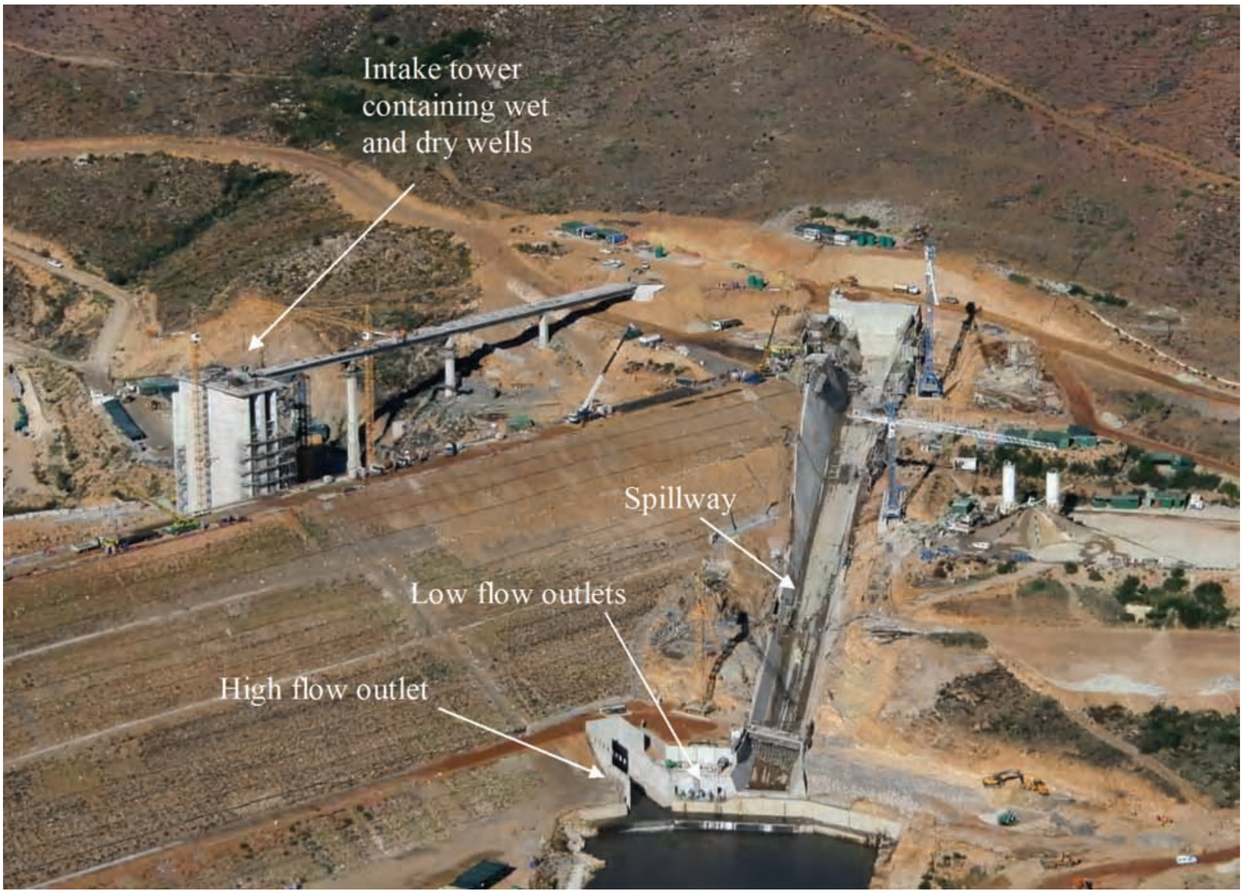


Figure 10-23 Intake tower and high and low flow outlets at Berg River Dam, under construction (photograph courtesy of Berg River Consultants)

A software release tool has been developed to facilitate the implementation of the low and high flow releases. The purpose of the tool is to assist the dam operator to make the required high and low flow releases at the appropriate time, with the desired hydrograph shape, magnitude and water temperature. The tool is linked to a Supervisory Control and Data Acquisition (SCADA) system, which provides it with real-time information on river flows and temperatures and on temperature profiles in the reservoir. For high flows, the inflows to the dam are monitored continuously and the operator is advised when a release is required. The operator then uses the tool to determine the shape of the hydrograph to be released, which level to draw water from and what the radial gate openings should be. Similarly for the low flows, the operator can use the tool to determine the release required and the level from which the water must be drawn (Abban et al.,2008).

10.3.3 Sediment flushing mechanisms for dams and weirs

The ability of a dam to pass sediment downstream is desirable from an infrastructure point of view to reduce sedimentation of the dam basin by allowing sediment transport through the dam and to maintain river morphology downstream. For dams smaller than about 0.03 MAR (very small in comparison to their MAR) sediment sluicing and flushing can be carried out during floods with relatively large bottom outlets, preferably with free flowing conditions (Beck and Basson, 2003). This is sustainable from a dam operation point of view, enabling a long-term equilibrium storage capacity to be attained. Successful sluicing requires excess water to be available and relatively large bottom outlets to be contained in the dam wall. Radial gates have been used for this purpose with success at First and Second Falls on the

Mtata River and with some success at Welbedacht Dam on the Caledon River and at Collywobles on the Mbhashe River.

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PART IV : CONCLUSION

11. CONCLUSIONS AND THE WAY FORWARD

11.1 Conclusions

This document provides a synthesis of existing knowledge on ecohydraulics in South Africa in terms of ecological context and perspective and the related hydraulic theories and techniques. The relationship between discharge and the availability of physical (hydraulic) habitat within the river ecosystem is highlighted and the role of ecohydraulics in predicting how the hydraulic habitat of specific species or communities might change under different development scenarios is defined.

The information contained in this document has again reiterated that the success of ecohydraulic applications depends on both the reliability of the water-biota correlations and the ability to model the occurrence of the water descriptors. Current hydraulic modeling capabilities are probably adequate for making the necessary linkages with the current knowledge of the dependence of biota on hydraulic characteristics, although improved resistance relationships for low flows and more representative velocity frequency distributions need to be developed. However, improving the confidence of hydraulic modeling predictions within an ecohydraulics context probably depends more on gaining a better understanding of biological responses than further development of hydraulic models

An evaluation of key linkages between river ecology and hydraulics conducted as part of this project, concluded that, although some of the ecological needs for hydraulic information are currently being met to a large extent, others have not been addressed in any form yet. It was found that the most comprehensive ecohydraulic inputs have been linked to maintenance of channel features and river depth-velocity relationships, with growing activity in the field of ecohydraulic modeling and hydraulic descriptors. Areas receiving little or no attention as yet are microhabitats and the hyporheos.

11.2 The Way Forward

The application of ecohydraulics in South Africa will benefit from developments in the following areas:

Hydraulic descriptors of aquatic habitat: Ecohydraulics involves the quantitative description of hydraulic variables to enable their association with ecological functioning. Models are available for doing this for a variety of variables over a range of scales and organizational levels. One important deficiency, however, is the ability for rigorous, quantitative description and prediction of biotopes or surface flow types, which are favoured by ecologists for characterizing ecologically relevant flow conditions. Hydraulic-biotope mapping provides an accessible form of information on the distribution of hydraulic habitats within a river reach in a way that is thought to be ecologically relevant and applicable for studying relationships between river flow and riverine biota. From the maps drawn they can be quantified by area per river reach and discharge, and their hydraulic attributes can be summarized in a fairly general way. However, biotopes are not well understood hydraulically and for this reason they are not presently compatible with hydraulic models. Whether or not they could be in the future, is a topic for research, as are the flow types that partially define them. Reliable methods are required for characterising the different types in meaningful hydraulic terms, describing their implicit hydraulic conditions, and predicting their occurrence and the way each type and the patchwork of their spatial arrangement changes with discharge.

Hydraulic modeling: Many ecological and hydraulic models in current use predict different aspects or components of river functioning and are restricted in application and scale. They do not account for the feedbacks inherent in the complexity of physical-biological interactions and their inputs and outputs are often incompatible and incommensurable. Development of a framework and strategy for coordinating models and their articulated use would enhance system understanding and management.

Flow resistance: The estimation of flow resistance in rivers remains a major source of uncertainty in the prediction of local hydraulic conditions. The innate variability of natural channels makes it difficult to formulate equations that realistically describe the underlying processes and necessitates a heavy reliance on empirical content. Developments are necessary in both the formulation of appropriate methods and strengthening of the empirical data bases. The equations presented in this Guide for large- and intermediate-scale roughness conditions have been verified under laboratory conditions, but require more substantial testing and possible modifications for field conditions. Conditions under which flow characteristics are determined by the occurrence of multiple local critical controls rather than resistance phenomena (e.g. in relatively steep channels with large roughness elements) need to be investigated, and prediction methods for these conditions need to be developed. One approach is to use statistical frequency-distribution methods, which could involve further testing of existing reach-scale models and the development (using 2-D hydraulic modeling) of morphological unit-scale methods for use in Reserve assessments. An effective and robust method for combining the effects of the different contributions to resistance over a river reach needs to be formulated. All appropriate developments and new data should be incorporated in the information system developed for South African rivers by Desai (Hirschowitz et al., 2007). The possibility of their incorporation in the Conveyance Estimation System developed by HR Wallingford (2004) should be explored as this would extend its usefulness for low flow conditions.

Habitat Suitability Criteria: Detailed studies of the localised hydraulic habitat requirements of aquatic biota are required. This information would inform the modeling of habitat hydraulics (e.g. the description of flow classes) in terms of relevant spatial scales and hydraulic detail.

Channel Maintenance Flows: Although the existing models that have been developed to quantify sediment flushing flows in cobble-bed rivers have been calibrated with extensive data sets, they have not been verified with field data. Before application of these models, it is imperative that the models are verified in the field, possibly by means of controlled reservoir releases.

Refinement of the Desktop Reserve model: Further development of the Desktop Reserve model to explicitly predict hydraulic conditions, flow indicator taxa and associated preferences for hydraulic habitat as a function of river condition.

Reserve monitoring: Development of appropriate techniques for assessing hydraulic and biophysical condition following Reserve implementation.

It is important to remember that ecohydraulics is still a relatively young science, which is inextricably linked to the sciences of environmental flow assessment and river rehabilitation. As the latter sciences are refined and developed, the role of ecohydraulics will continue to evolve in parallel with this process.

11.3 References

Hirschowitz, P M, Birkhead, A L and Janes, C S. 2007. Hydraulic modeling for ecological studies for South African rivers. WRC Report No 1508/1/07. Water Research Commission, Pretoria, South Africa.

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