ENVIRONMENTALLY SIGNIFICANT MORPHOLOGICAL AND HYDRAULIC CHARACTERISTICS OF COBBLE AND BOULDER BED RIVERS IN THE WESTERN CAPE

V Jonker • A Rooseboom • AHM Görgens

WRC Report No. 979/ 1/01

Water Research Commission

ENVIRONMENTALLY SIGNIFICANT MORPHOLOGICAL AND HYDRAULIC CHARACTERISTICS OF COBBLE AND BOULDER BED RIVERS IN THE WESTERN CAPE

by

V. JONKER, A. ROOSEBOOM and A.H.M GöRGENS

Department of Civil Engineering
University of Stellenbosch
Stellenbosch

Report to the Water Research Commission on the Project:

"Hydraulic characteristics of ecological flow requirement components in winter rainfall rivers"

Project Leader : Professor AHM Görgens

WRC Report No. 979/1/01
ISBN No. 1 86845 735 4

May 2002

EXECUTIVE SUMMARY

Background and Motivation

The development and management of water resources have altered the natural flow regimes of most rivers around the world and have led to a growing concern regarding the deterioration of river environments. A new scientific tool, known as Environmental (or Instream) Flow Assessment, has been developed, to predict the aquatic environmental impacts associated with water resources developments and to provide information on the magnitudes and frequency of flows which are required to maintain the river in a pre-determined, environmentally acceptable condition (King and Tharme, 1994). This then serves as a guideline for managing the river in terms of operating rules for dams or water diversions for example, while at the same time providing for the ecological requirements of the riverine ecosystem. The essence of these assessments is "to identify those fundamental components of a river's flow regime that are considered essential for perpetuation of its valued ecological or water resource features, and to negotiate for these to be built into a modified flow regime" (King and Tharme, 1994). Various environmental flow assessment techniques have been developed and are continuously being refined. Generally, these techniques are based on the interpretation of hydrological, hydraulic and biological data. Flow discharge values are translated into local hydraulic conditions, thus allowing determination of how the physical habitat changes with discharge and how this affects the habitat preferences of different species.

The interaction between moving water and the physical attributes of a river, as described by the channel morphology, determines ecosystem functioning through the availability of physical (hydraulic) habitat for aquatic species. It is therefore essential to understand the mechanisms controlling local hydraulic parameters to predict the effect of altering the flow and sediment regime on a river (Broadhurst *et al.*, 1997). In South Africa, the need for an understanding of the links between local hydraulic conditions, channel morphology and riverine ecosystem structure, was recognized by Rogers *et al.* (1992) as part of an integrated, holistic research programme in the Kruger National Park. The need to establish these links has been further highlighted with the development of the "ecohydraulics" concept, which has evolved to study the links between physical (mainly hydraulic) conditions in a river and biotic distributions (Newson *et al.*, 1998), and which places great emphasis on the diversity or the mosaic of hydraulic conditions within a reach.

Various research projects, which – to a greater or lesser extent – address the link between channel morphology, hydraulic characteristics and the biotic environment, have been initiated in South Africa. These include: an assessment of channel flow resistance on the Sabie River in order to link hydrological data to hydraulic variables (Broadhurst *et al.*, 1997); the development of a hierarchical geomorphological model for the classification of selected South African rivers (Wadeson and Rowntree, 1999), which presents a framework within which the impacts of water management on channel form and associated ecological processes can be assessed; and an empirical linkage of abiotic and biotic patterns on a regional basis to determine whether the geomorphological character of a river is a useful guide to its ecological character (King and Schael, 2001).

It is within this context that the current research was initiated in order to determine the environmentally significant morphological and hydraulic characteristics of cobble and boulder bed rivers in the Western Cape. With the increasing development of water-related infrastructure in mountain regions, knowledge of the hydraulic characteristics of rivers in the upper catchment areas is very important. Cobble and boulder bed rivers in the Western Cape are typical examples. They are characterized by steep gradients, great variability in sediment size and relatively low flow depths. The bed configuration displays a series of pools, steps, rapids, riffles and plane beds, while energy losses are high as a result of turbulence and local hydraulic jumps. Due to their characteristic morphological and associated hydraulic attributes, the physical habitats within these rivers are extremely diverse, both on a spatial and temporal scale.

Objectives

The original project aims as formulated in the project proposal, were:

i. To determine regional patterns in hydraulic characteristics of the individual components of ecological flow requirements in rivers of the winter rainfall region.
ii. To derive a universally applicable methodology to calculate energy losses in streamflow in cobble bed rivers of the winter rainfall region in order to determine stage discharge relationships.
iii. To determine the hydraulic characteristics of winter rainfall region monitoring sites used in the WRC project on Biotic-Abiotic Links conducted by the Freshwater Research Unit of the University of Cape Town.

As the project progressed it became clear that in order to describe the hydraulic and morphological related characteristics of environmental flow components in cobble and boulder bed rivers of the Western Cape, the original aims needed to be revisited. Modified objectives, which can be considered as refinements of aims i and ii, were subsequently formulated. (Aim no. iii as referred to above, was considered separately from the main research programme and a report, which specifically addresses the hydraulic characteristics of winter rainfall region monitoring sites used in the WRC project on Biotic-Abiotic Links, was submitted to the Freshwater Research Unit at the University of Cape Town).

The revised objectives were as follows: (A brief motivation is provided in each case)

i. **To predict the impact of a modified flow regime on the morphological characteristics of cobble and boulder bed rivers.**

A characteristic morphological feature of cobble and boulder bed rivers is the presence of macro scale bed forms, e.g. pools, rapids and riffles and the general absence of smaller scale bed forms which may include ripples, dunes, etc. Due to the presence of these bed forms and their associated hydraulic attributes, the physical habitat associated with cobble and boulder bed rivers is extremely diverse, both on a spatial and temporal scale. Maintaining the morphological character of cobble and boulder bed rivers is therefore an important prerequisite for sustainable ecosystem functioning, as it is the interaction between channel morphology and the moving water which determines the availability of physical (hydraulic) habitat for aquatic species. Therefore, in order to predict the environmental impacts associated with a modified flow regime, an understanding of the relationship between the channel forming discharge and the ecologically relevant morphological attributes is required.

ii. **To develop a sand scour model for cobble bed rivers which predicts the depth and rate of sand scour.**

In cobble bed rivers many aquatic species are dependent on the interstitial spaces between the cobbles for their survival. The accumulation of fine sands in cobble bed rivers, which fill these interstitial spaces, can therefore have a detrimental effect on the whole aquatic ecosystem. The construction of reservoirs leads to a decrease in flood peaks and flooding frequency as well as sediment transport capacity in the river channels downstream. Fine sands introduced into this part of the river system from the incremental catchment downstream of the reservoir, may therefore accumulate on parts of the river bed. In order to flush these unwanted fine sands from the interstitial spaces between the cobbles and gravels downstream of reservoirs, special reservoir releases known as flushing flows or sediment maintenance flows need to be specified. A scour model, which predicts the maximum depth of scour as well as the rate of scour of fine sands in a cobble bed in terms of time and discharge dependent relationships, therefore needs to be developed.

iii. To derive a generally applicable methodology for calculating stage discharge relationships under conditions of large scale roughness

Due to the different hydraulic processes of flow resistance under conditions of large scale roughness, when the flow depth and the bed particles are of the same order of magnitude, the conventional friction based formulae, such as Manning and Chézy, have been found to underestimate channel roughness considerably. This is typically the case in cobble and boulder bed rivers, which are characterized by steep gradients and relatively low flow depths in relation to bed particle size. A generally applicable methodology for calculating stage discharge relationships under conditions of large scale roughness will therefore be developed.

iv. To determine the low flow hydraulic characteristics of cobble and boulder bed rivers and their relationship to the aquatic habitat.

During low flow conditions in cobble and boulder bed rivers, where the effect of large-scale roughness is dominant, complex flow patterns develop and the average, cross-sectional hydraulic parameters as such do not represent the diversity of local hydraulic conditions and associated habitat types occurring within the reach. The description of the aquatic habitat in freshwater ecosystems requires information on the spatial variability of hydraulic conditions within a reach, which bridges the gap between the reach scale, which is appropriate for a reliable simulation of average hydraulic conditions, and the local scale, at which habitat preferences occur. Zones or areas within which similar hydraulic patterns occur will therefore be identified by determining the local hydraulic characteristics of low flows in cobble and boulder bed rivers and by using statistical methods to describe their distribution within a morphological framework.

Results

The research output includes a collection of rapid assessment tools, which can be used during the pre-feasibility and feasibility stages of water resources planning for determining the hydraulic and morphological characteristics of individual environmental flow components in cobble and boulder bed rivers of the Western Cape. Environmental flow components specifically addressed are channel forming flows (Objective i), sediment maintenance or flushing flows (Objective ii) and the hydraulic and habitat characteristics of low flows (Objective iv).

- **A regime model for cobble and boulder bed rivers**

  (Objective i: To predict the impact of a modified flow regime on the morphological characteristics of cobble and boulder bed rivers.)

A regime model was developed to address the regime characteristics of cobble and boulder bed rivers. The model defines the relationship between the channel forming discharge and those morphological attributes which have special ecological significance, e.g. substrate characteristics, the local gradient of riffles and rapids which affect turbulence and the spacing or frequency of bed forms. The model, which can be classified as a rational regime model, is based on the hypothesis that the formation of pools and riffles is essentially a mechanism of self-adjustment by the stream system towards obtaining dynamic equilibrium, i.e. at a characteristic discharge and bed particle size distribution, the river adjusts its width, average gradient, local gradient of the riffle or rapid, absolute bed roughness and flow depth until equilibrium exists in terms of the power applied along the bed and the power required to suspend bed particles as well as in terms of momentum exchange between the accelerating water along the riffle and the slower moving water in the pool. This behaviour is comparable to the formation of bed forms in sand bed rivers, where flow resistance is increased in order to dissipate excess energy and to limit the scouring of sand from the river bed (Rooseboom and Le Grange, 2000).

- **A sand scour model for cobble bed rivers**

  (Objective ii: To develop a sand scour model for cobble bed rivers which predicts the depth and rate of sand scour.)

A scour model, which is founded on the law of conservation of stream power, was developed, which predicts the maximum depth of scour as well as the rate of scour of fine sands in a cobble bed in terms of time and discharge dependent relationships. The maximum scour depth represents the level below the top of the cobbles at which no further scour is observed, while the rate of scour refers to the progression of the scour level below the top of the cobbles. The model has been developed from a model defining the condition of dynamic equilibrium for steady state sediment transport in a sand bed river. With the aid of physical model studies in the hydraulics laboratory, distinct relationships were derived between the absolute roughness or maximum depth of scour, sand particle characteristics and the relative applied power.

- **Stage discharge relationships**

  (Objective iii: To derive a generally applicable methodology for calculating stage discharge relationships in cobble and boulder bed rivers)

A fundamental approach towards the estimation of mean velocity under conditions of large scale roughness led to the development of a relatively simple and generally applicable equation. With the aid of an extensive dataset from literature, the resistance coefficient in this equation (C_s) was calibrated and it was found that C_s displays a good correlation with relative submergence (R/d_{50}) and displays less variability across different rivers and reaches than the Darcy Weisbach resistance coefficient (f), which is usually used to quantify flow resistance under conditions of large scale roughness. The application of this new equation to cobble and boulder bed rivers in the Western Cape, proved that it is able to provide a fairly accurate estimate of mean flow velocity under conditions of large scale roughness and can therefore be used for obtaining first order estimates of stage discharge relationships during the environmental flow assessment process.

- **Low flow hydraulic characteristics in cobble and boulder bed rivers and their relationship to the aquatic habitat**

(Objective iv: To determine the low flow hydraulic characteristics of cobble and boulder bed rivers and their relationship to the aquatic habitat.)

It was found that the average hydraulic conditions within cobble and boulder bed rivers are inadequate for representing the diversity of local hydraulic conditions within a reach. Not only are reaches characterized by different types of morphological units, each associated with unique hydraulic characteristics, but, due to the effect of large scale roughness, the hydraulic conditions within each morphological unit also vary considerably. Furthermore, it was shown that the dominant morphological unit types in cobble and boulder bed rivers of the Western Cape, i.e. pool, plane bed, rapid and riffle morphological units, display significant variability in terms of their habitat diversity, with rapid and riffle morphological units characterized by a wider range of biotope classes and flow types than plane bed and pool morphological units. Finally, it was demonstrated that different hydraulic biotope classes and flow types may be classified in terms of their hydraulic characteristics. However, it was found that similar biotope classes and flow types display different hydraulic characteristics depending on the type of morphological unit in which they are situated. This implies that the hydraulic classification of habitat types and flow types in cobble and boulder bed rivers needs to accommodate the type of morphological unit within which they occur.

A statistical, velocity distribution model was developed for predicting the probability distribution of local flow velocities in cobble and boulder bed rivers during low flows. It was found that the distribution of local sets of point velocities within pool, rapid and riffle morphological units may be related to average cross-sectional hydraulic parameters (e.g. Froude number, Reynolds number, the velocity/depth ratio, the width/depth ratio and the relative roughness). For plane bed morphological units, no statistically significant relationships were found.

Conclusions

In essence, this research programme addressed the interaction between moving water and the physical attributes of cobble and boulder bed rivers, and as such provides a link between the macro scale morphological characteristics and the local (biotope) scale, ecologically significant hydraulic characteristics of these rivers. The objectives which were defined at the start of the research programme, have been met through the development of empirical, semi-empirical and theoretically based models, which define the hydraulic and morphological related characteristics of individual environmental flow components. These models, which may serve as tools for determining the hydraulic and morphological characteristics of individual environmental flow components in the cobble and boulder bed rivers of the Western Cape, mainly address:

- the regime characteristics of cobble and boulder bed rivers
- fine sand scouring in cobble beds
- stage-discharge relationships under conditions of large scale roughness, and
- low flow hydraulic characteristics of cobble and boulder bed rivers and their relationship to the aquatic habitat.

Practical guidelines for the application of these models have been developed.

The main conclusions that have been reached are:

- In the longitudinally concave-shaped, alluvial rivers of the Western Cape, cobble and boulder bed reaches typically occur in the mountain transitional zone, as well as in the upper and lower foothill zones. These reaches are characterized by four dominant types of morphological units, viz. pools, plane beds, riffles and rapids.
- The process of macro scale bed deformation in cobble and boulder bed rivers may be considered as a means of self adjustment towards obtaining dynamic equilibrium. The river bed transforms its profile into a series of consecutive macro scale bed forms in order to create natural control structures, each of which forces the water through critical depth with a subsequent hydraulic jump downstream. This deformation continues until equilibrium exists in terms of the power applied along the bed and the power required to suspend bed particles as well as in terms of momentum exchange between the accelerating water along the riffle and the slower moving water in the pool.
- The process of scouring of fine sands in a cobble bed and the associated change in absolute bed roughness, is similar to the process of bed deformation in a sand bed river, and may be defined by relationships similar to those that exist between absolute bed roughness and particle characteristics under conditions of dynamic equilibrium on a deformed sand bed river.
- A fundamental approach towards the estimation of mean velocity under conditions of large scale roughness led to the development of a relatively simple and generally applicable equation. The application of this new equation to cobble and boulder bed rivers in the Western Cape, proved that it is able to provide a fairly accurate estimate of mean

flow velocity under conditions of large scale roughness and can therefore be used for obtaining first order estimates of stage discharge relationships during the environmental flow assessment process.

- During low flows, the average hydraulic conditions within these reaches are inadequate for representing the diversity of local hydraulic conditions within the reach. Not only is each type of morphological unit associated with unique hydraulic characteristics, but, due to the effect of large scale roughness, the hydraulic conditions within each morphological unit also vary considerably.
- Each type of morphological unit displays significant variability in terms of its habitat diversity, with rapid and riffle morphological units characterized by more biotope classes and flow types than plane bed and pool morphological units.
- Biotope classes and flow types in cobble and boulder bed rivers may be classified in terms of their hydraulic characteristics. However, similar biotope classes and flow types display different hydraulic characteristics depending on the type of morphological unit in which they are situated. This implies that the hydraulic classification of habitat types in cobble and boulder bed rivers needs to accommodate the type of morphological unit within which they occur.

Recommendations

Based on the findings of this research programme, the following general recommendations can be made:

- Although all the models that have been developed as part of this research programme have been calibrated with extensive data sets, they have not, with the exception of the stage-discharge model, been verified with independent data sets. Before application of these models, it is therefore imperative that:
    - the ability of the regime model to predict channel deformation is verified over a range of reach types and bed particle sizes. This may include laboratory studies.
    - the sand scour model be verified in the field, possibly by means of controlled reservoir releases. The effects of absolute cobble size, non-uniform cobble size and steady state sediment transport conditions need to be investigated.
    - the velocity distribution model be verified with additional field data and possibly further refined by introducing additional explanatory variables.

- As an additional verification exercise, it is recommended that the models which have been developed are used to determine the morphological and hydraulic characteristics of environmental flow components as specified in rivers where an environmental flow assessment has already been completed.
- It is recommended that the classification of habitat types in cobble and boulder bed rivers be expanded to accommodate the effect of morphological unit type. Furthermore a mathematical or statistical function, a "diversity index", should be developed, which will allow the quantification of habitat diversity per morphological unit, based on the assortment of biotope classes or flow types. This will allow the effect of a changing discharge regime on habitat characteristics to be anticipated.

CAPACITY BUILDING

As engineers and ecologists have historically tended to operate in a poorly integrated manner, this project was recognised as an excellent opportunity to provide a multi-disciplinary environment for capacity building in ecological resource management, in an engineering context.

In this regard, the following meetings have taken place during the report period :

- Meetings with Dr JM King, Freshwater Research Unit, University of Cape Town
- Meeting with Prof K Rowntree, Institute for Water Research, Rhodes University
- Meeting with Prof J O'Keeffe, Institute for Water Research, Rhodes University
- Meeting with Ms DM Schael, University of Port Elizabeth, Zoologist
- Field visit with Dr JM King, University of Cape Town

Numerous informal discussions with these scientists have also taken place during the report period.

The report also provided opportunities for capacity building in terms of previously disadvantaged individuals. A student from the Peninsula Technikon, Tando Zitumane, who completed her practical training at the University of Stellenbosch, assisted with laboratory work, while two female students, Gyonne Quemer from the Christelijke Hogeschool Windesheim in the Netherlands and Mia van Wyk, a post graduate student at the Department of Civil Engineering at the University of Stellenbosch, assisted with field work, laboratory experiments and data analyses.

ENVIRONMENTALLY SIGNIFICANT MORPHOLOGICAL AND HYDRAULIC CHARACTERISTICS OF COBBLE AND BOULDER BED RIVERS IN THE WESTERN CAPE

TABLE OF CONTENTS

III. ENVIRONMENTALLY SIGNIFICANT HYDRAULIC CHARACTERISTICS OF COBBLE AND BOULDER BED RIVERS IN THE WESTERN CAPE

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF SYMBOLS

a,b	: constants
A	: cross-sectional flow area
A_p	: wetted frontal area of a bed particle
A_w	: wetted roughness cross-sectional area
b	: roughness concentration
b_e	: function of effective roughness concentration
c	: resistance coefficient
C	: Chézy resistance coefficient
C_d	: drag coefficient
C_k	: kinetic energy loss coefficient
$C\ell$	: transition energy loss coefficient
C_m	: mobility coefficient
C_s	: large scale roughness resistance coefficient
d	: particle diameter
d_x	: particle size for which x % is smaller
D	: flow depth
$\bar{D}$	: mean flow depth over cross section
D_{ch}	: channel depth at bankfull level
f	: Darcy-Weisbach resistance coefficient
Fr	: Froude number
F_f	: external frictional force exerted by boundaries
g	: gravitational acceleration
h_f	: friction loss
h_ℓ	: transition loss
H	: total head
j	: shape parameter
k	: absolute bed roughness
ℓ	: reach length
L	: spacing of pools and riffles/rapids
m	: mass of unit volume of water
n	: Manning resistance coefficient
n^*	: number of bed particles in reach of length ℓ
n_ℓ	: number of bed particles along a streamline in reach of length ℓ
n_w	: number of vertical elements in cross section
P	: wetted perimeter
P_x	: water pressure force at section x
Q	: discharge
Q_{bf}	: discharge at bankfull level
Q_c	: characteristic discharge
Q_m	: measured discharge
Q_s	: sediment discharge
Q_x	: discharge with return period equal to x
R	: hydraulic radius
R_e	: Reynolds number
R_e^*	: Roughness Reynolds number
R_0	: radius of a turbulent eddy next to the bed
R_d	: radius of eddy
R_s	: rate of sand scour
s	: energy gradient ≈ channel gradient (under uniform flow conditions)
S_f	: energy gradient
S_0	: average channel gradient
t	: time for water to move distance equal to one cobble diameter
v	: local flow velocity
V	: average velocity over cross section
V^*	: shear velocity
V^*_{cr}	: critical shear velocity

V_{ss} : settling velocity

V_0 : translatory velocity of the centre of rotation

v_{max} : maximum flow velocity within cross section

w : weight of water

W_{ch} : channel width at bankfull level

W_T : flow width

W : flow width

x_a, x_b : constants

x_1 : parameter defining the relationship between C_f and d/D

x_2 : parameter defining the relationship between C_k and d/D

y : flow depth

y_c : critical flow depth

y_i : initial flow depth

y_n : uniform flow depth

y_s : sequent flow depth

y_0 : ordinate where the velocity is mathematically equal to zero

$\overline{y_0}$: mean ordinate value over the cross section where the velocity is mathematically = 0

z : bed elevation above datum

α : energy correction factor

α_r : local riffle/rapid gradient

α_{WB} : scale parameter (Weibull distribution)

α_{EXT} : scale parameter (Extreme Type I distribution)

β : momentum correction factor

β_{WB} : shape parameter (Weibull distribution)

β_{EXT} : location parameter (Extreme Type I distribution)

θ : channel slope

θ_c : dimensionless parameter

κ : von Karman coefficient

ϕ : angle of repose

μ : statistical mean

ρ : density of water

ρ_s : particle density

σ : standard deviation

ν : kinematic viscosity of water

τ : shear stress

τ_c : critical shear stress

Δz : measured pool depth

Δ : non-dimensional parameter reflecting the increase in bed roughness until equilibrium is reached

LIST OF ACRONYMS

EFA : Environmental Flow Assessment

EFR : Environmental Flow Requirement

BBM : Building Block Methodology

IFIM : Instream Flow Incremental Methodology

WUA : Weighted Usable Area

DRIFT : Downstream Response to Imposed Flow Transformations

ROIP : Relevant Environmental Impact Prognosis

SD : Standard deviation

SE : Standard error of estimate

GLOSSARY

Environmental flow assessment
The process of determining the quantity of water which is required for the environmental needs of a river.

Environmental flow requirement
The quantity of water required in a modified flow regime, which is deemed necessary for maintaining a river in a pre-determined, environmentally acceptable condition.

Environmental flow component
Flows of different timing and duration encompassed in an environmental flow requirement, with the aim of simulating the fundamental character encompassed in the natural flow regime of a river.

Uniform flow
Flow characterized by a constant water depth, flow area and flow velocity and by equilibrium in terms of the resistance and gravity forces.

Threshold condition
The critical condition for the initiation of movement of sediment particles on a river bed.

Bedrock channels
River channels characterized by the absence of alluvial sediment, except in isolated scour holes.

Alluvial channels
River channels which pass through sediments that they have previously deposited.

Morphological unit
The basic structure or building block comprising the channel morphology – either an erosional or depositional feature.

Regime channel
An open flow channel where equilibrium exists between the flow rate, the channel form, the transport of sediment and the channel gradient.

Stage discharge relationship
The relationship between flow depth and flow rate at a specific cross section within a river.

Flow resistance
The resistance to flow encountered by water as it flows in a river channel.

Relative submergence
The ratio of the mean flow depth or the hydraulic radius to absolute bed roughness (represented by a characteristic bed particle size).

Relative roughness
The ratio of absolute bed roughness (represented by a characteristic bed particle size) to the mean flow depth or the hydraulic radius.

Large scale roughness
Describes flow resistance when the flow depth and bed particles are of the same order of magnitude.

Hydraulic biotope
A spatially distinct instream flow environment characterized by specific hydraulic attributes that provides the abiotic environment in which species assemblages or communities live.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission, entitled:

HYDRAULIC CHARACTERISTICS OF ECOLOGICAL FLOW REQUIREMENT COMPONENTS IN WINTER RAINFALL RIVERS

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

Mr DS Van der Merwe	: Water Research Commission (Chairman)
Mr OCE Hempel	: Water Research Commission (Secretary)
Dr SA Mitchell	: Water Research Commission
Prof AHM Görgens	: University of Stellenbosch
Prof A Rooseboom	: University of Stellenbosch
Prof G Basson	: University of Stellenbosch
Mr V Jonker	: University of Stellenbosch
Prof C James	: University of the Witwatersrand
Prof GGS Pegram	: University of Natal
Dr JM King	: University of Cape Town
Dr CJ Kleynhans	: Department of Water Affairs and Forestry
Dr A Birkhead	: University of the Witwatersrand
Mr NP Armitage	: University of Cape Town

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged gratefully.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the following:

- Dr JM King of the University of Cape Town for use of the flow meter as well as her invaluable inputs during numerous informal discussions.
- Professors K Rowntree and J O'Keeffe of Rhodes University for the sharing of their knowledge and ideas.
- Cape Nature Conservation for permission to collect data in conservation areas.
- The Department of Water Affairs and Forestry who provided information on rating curves.

- Ninham Shand Consulting Engineers for providing assistance with the compilation of the final report.
- SAFCOL for permission to collect data within afforested areas.
- The students who assisted with field and laboratory work as well as data analysis, viz. J Malan, G Querner, C van der Bosch, T Zitumane, J Brandt, S Martin, J Wissmann and M van Wyk.

1. BACKGROUND

1. INTRODUCTION

1.1. Background

The development and management of water resources have altered the natural flow regimes of most rivers around the world and have led to a growing concern regarding the deterioration of river environments. A new scientific tool, known as Environmental (or Instream) Flow Assessment, has been developed, to predict the aquatic environmental impacts associated with water resources developments and to provide information on the magnitudes and frequency of flows which are required to maintain the river in a pre-determined, environmentally acceptable condition (King and Tharme, 1994). This then serves as a guideline for managing the river in terms of operating rules for dams, water diversions etc., while at the same time providing for the ecological requirements of the riverine ecosystem. The essence of these assessments is "to identify those fundamental components of a river's flow regime that are considered essential for perpetuation of its valued ecological or water resource features, and to negotiate for these to be built into a modified flow regime" (King and Tharme, 1994). Various environmental flow assessment techniques have been developed and are continuously being refined. Generally, these techniques are based on the interpretation of hydrological, hydraulic and biological data. Hydrological data, in the form of simulated, daily discharges, must be translated into local hydraulic conditions (Broadhurst *et al.*, 1997). It can thus be determined how the physical habitat changes with discharge and how this affects the habitat preferences of different species.

The interaction between moving water and the physical attributes of a river, as described by the channel morphology, determines ecosystem functioning through the availability of physical (hydraulic) habitat for aquatic species. It is therefore essential to understand the mechanisms controlling local hydraulic parameters to predict the effect of altering the flow and sediment regime on a river (Broadhurst *et al.*, 1997). In South Africa, the need for an understanding of the links between local hydraulic conditions, channel morphology and riverine ecosystem structure, was recognized by Rogers *et al.* (1992) as part of an integrated, holistic research programme in the Kruger National Park. The need to establish these links has been further highlighted with the development of the "ecohydraulics" concept, which has evolved to study the links between physical (mainly hydraulic) conditions in a river and biotic distributions (Newson *et al.*, 1998), and which places great emphasis on the diversity or the mosaic of hydraulic conditions within a reach.

In South Africa, various research projects, which – to a greater or lesser extent – address the link between channel morphology, hydraulic characteristics and the biotic environment, have been initiated. These include : an assessment of channel flow resistance on the Sabie River in order to link hydrological data to hydraulic variables (Broadhurst *et al.*, 1997); the development of a hierarchical geomorphological model for the classification of selected South African rivers (Wadeson and Rowntree, 1999), which presents a framework within which the impacts of water management on channel form and associated ecological processes can be assessed; and an empirical linkage of abiotic and biotic patterns on a regional basis to determine whether the geomorphological character of a river is a useful guide to its ecological character (King and Schael, 2001).

It is within this context that the current research was initiated in order to determine the environmentally significant morphological and hydraulic characteristics of cobble and boulder bed rivers in the Western Cape. With the increasing development of water-related infrastructure in mountain regions, knowledge of the hydraulic characteristics of rivers in the upper catchment areas is very important. Cobble and boulder bed rivers in the Western Cape are typical examples. They are characterized by steep gradients, great variability in sediment size and relatively low flow depths. The bed configuration displays a series of pools, steps, rapids, riffles and plane beds, while energy losses are high as a result of turbulence and local hydraulic jumps. Due to their characteristic morphological and associated hydraulic attributes, the physical habitats within these rivers are extremely diverse, both on a spatial and temporal scale.

1.2 Objectives

The original project aims as formulated in the project proposal, were:

i. To determine regional patterns in hydraulic characteristics of the individual components of ecological flow requirements in rivers of the winter rainfall region.

ii. To derive a universally applicable methodology to calculate energy losses in streamflow in cobble bed rivers of the winter rainfall region in order to determine stage discharge relationships.

iii. To determine the hydraulic characteristics of winter rainfall region monitoring sites used in the WRC project on Biotic-Abiotic Links conducted by the Freshwater Research Unit of the University of Cape Town.

As the project progressed it became clear that in order to describe the hydraulic and morphological related characteristics of environmental flow components in cobble and boulder bed rivers of the Western Cape, the original aims needed to be revisited. Objectives, which can be considered as refinements of aims i and ii, were subsequently formulated. (Aim no. iii as referred to above, was considered separately from the main research programme and a report which specifically addresses the hydraulic characteristics of winter rainfall region monitoring sites used in the WRC project on Biotic-Abiotic Links was submitted to the Freshwater Research Unit at the University of Cape Town (attached as Appendix A).)

The revised objectives were as follows: (A brief motivation is provided in each case)

1. **To predict the impact of a modified flow regime on the morphological characteristics of cobble and boulder bed rivers.**

   A characteristic morphological feature of cobble and boulder bed rivers is the presence of macro scale bed forms, e.g. pools, rapids and riffles and the general absence of smaller scale bed forms which may include ripples, dunes, etc. Due to the presence of these bed forms and their associated hydraulic attributes, the physical habitat associated with cobble and boulder bed rivers is extremely diverse, both on a spatial and temporal scale. Maintaining the morphological character of cobble and boulder bed rivers is therefore an important prerequisite for sustainable ecosystem functioning, as it is the interaction between channel morphology and the moving water which determines the availability of physical (hydraulic) habitat for aquatic species. Therefore, in order to predict the environmental impacts associated with a modified flow regime, an understanding of the relationship between the channel forming discharge and the ecologically relevant morphological attributes is required.

2. **To develop a sand scour model for cobble bed rivers which predicts the depth and rate of sand scour.**

   In cobble bed rivers many aquatic species are dependent on the interstitial spaces between the cobbles for their survival. The accumulation of fine sands in cobble bed rivers, which fill these interstitial spaces, can therefore have a detrimental effect on the whole aquatic ecosystem. The construction of reservoirs leads to a decrease in flood peaks and flooding frequency as well as sediment transport capacity in the river channels downstream. Fine sands introduced into this part of the river system from the incremental catchment downstream of the reservoir, may therefore accumulate on parts of the river bed. In order to flush these unwanted fine sands from the interstitial spaces between the cobbles and gravels downstream of reservoirs, special reservoir releases known as flushing flows or sediment maintenance flows need to be specified. A scour model, which predicts the maximum depth of scour as well as the rate of scour of fine sands in a cobble bed in terms of time and discharge dependent relationships, therefore needs to be developed.

3. **To derive a generally applicable methodology for calculating stage discharge relationships in cobble and boulder bed rivers**

   Due to the different hydraulic processes of flow resistance under conditions of large scale roughness, when the flow depth and the bed particles are of the same order of magnitude, the conventional friction based formulae, such as Manning and Chézy, have been found to underestimate channel roughness considerably. This is typically the case in cobble and boulder bed rivers, which are characterized by steep gradients and relatively low flow depths in relation to bed particle size. A generally applicable methodology for calculating stage discharge relationships in cobble and boulder bed rivers of the Western Cape will therefore be developed.

4. **To determine the low flow hydraulic characteristics of cobble and boulder bed rivers and their relationship to the aquatic habitat.**

   During low flow conditions in cobble and boulder bed rivers, where the effect of large-scale roughness is dominant, complex flow patterns develop and the average, cross-sectional hydraulic parameters as such do not represent the diversity of local hydraulic conditions and associated habitat types occurring within the reach. The description of the aquatic habitat in freshwater ecosystems requires information on the spatial variability of hydraulic conditions within a reach, which bridges the gap between the reach scale, which is appropriate for a reliable simulation of average hydraulic conditions, and the local scale, at which habitat preferences occur. Zones or areas within which similar hydraulic patterns occur will therefore be identified by determining the local hydraulic characteristics of low flows in cobble and boulder bed rivers and by using statistical methods to describe their distribution within a morphological framework.

All of these objectives were met and the research product includes a collection of rapid assessment tools, which can be used during the pre-feasibility and feasibility stages of water resources planning for determining the hydraulic characteristics of individual environmental flow components in cobble and boulder bed rivers of the Western Cape. Environmental flow components specifically addressed are channel forming flows (Objective 1), sediment maintenance or flushing flows (Objective 2) and the hydraulic and habitat characteristics of low flows (Objective 4).

1.3 Layout

The report has been structured to consist of three parts, viz.:

I. Background

This section provides general information regarding the research project, as well as introductions to environmental flow assessment, basic river hydraulics and channel morphology.

II. The environmentally significant morphological characteristics of cobble and boulder bed rivers in the Western Cape

Objectives 1 and 2 are addressed within this section which includes the development of regime and sand scour models for cobble and boulder bed rivers.

III. The environmentally significant hydraulic characteristics of cobble and boulder bed rivers in the Western Cape

This section concerns objectives 3 and 4, i.e. stage-discharge relationships under conditions of large scale roughness, the hydraulic characteristics of low flows in cobble and boulder bed rivers and the hydraulic classification of aquatic habitats.

The report closes with guidelines for the application of the research results, final conclusions and recommendations.

2. ENVIRONMENTAL FLOW ASSESSMENT

2.1 Introduction

Instream flows are those flows that are retained in their natural flowpaths as opposed to water which is diverted for "offstream" uses such as irrigation, industry etc. Instream flows are important for maintaining the habitat of aquatic and riparian ecosystems, but can also support economically important activities such as transportation, production of hydroelectricity and waste disposal. These ecosystems are best preserved under natural, pristine conditions. However, the development and management of water resources for human utilisation have altered the natural flow regimes of most rivers around the world. A new scientific discipline has therefore been developed to predict the biological impacts associated with water resources developments and to provide information on the flows that are required in a particular river in order to maintain the river in a pre-determined, environmentally acceptable condition. This then serves as a guideline for managing the river in terms of operating rules for dams, water diversions etc., while still providing for the ecological requirements of the riverine ecosystem.

The process of determination of the amount of water which is required for environmental needs, is known as an "Environmental Flow Assessment" (EFA). Following the EFA, a modified flow regime is prescribed for the river. The amount of water required in the modified flow regime is that which is deemed to be necessary for maintaining the river in a pre-determined condition and is known as the "Environmental Flow Requirement" (EFR). EFR's are based on an understanding (Brown and King, 2000) of how flow changes relate to changes in river condition, which can be used to describe flows that will:

- minimize or mitigate the impacts of a new water-resource development
- restore systems impacted by past developments
- allow calculation of the costs of compensating people affected by such impacts.

In general, the closer to natural the desired condition of the aquatic system, the greater the fraction of the original flow regime that will be required as an EFR (Figure 2.1).

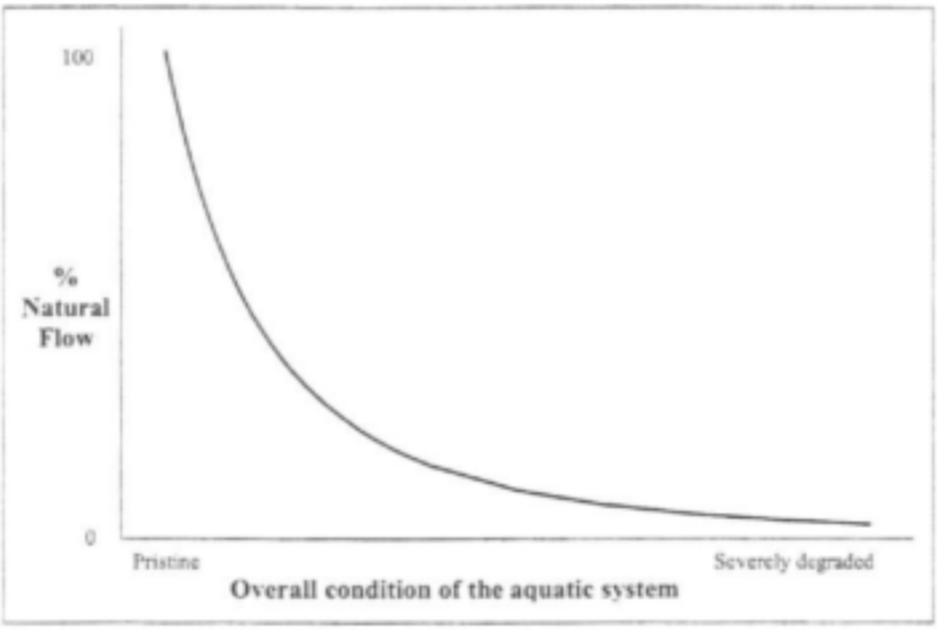


Figure 2.1 : Schematic illustrating the relationship between percentage of natural flow and river condition (Brown and King, 2000)

2.2 Environmental flow components

As indicated in Table 2.1, which describes the importance of different flow components from an ecological perspective, different parts of the flow regime elicit different habitat-related responses from a river. King and Louw (1998) list the most important characteristics of the natural flow regime of a river as:

- degree of perenniality
- magnitude of the low flows in the dry and wet season
- magnitude, timing and duration of floods in the wet season
- small floods that occur in the drier months

The normal low flows in the river outside of floods.	Low flows define the basic seasonality in rivers – its dry and wet season, whether it flows all year or dries out for part of it. The different magnitudes of low flows in the dry and wet seasons create more or less wetted habitat and different hydraulic and chemical conditions, which directly influence what the balance of species will be in any season.
Freshes: small floods that occur several times within a year.	Defined here as small pulses of higher flow, freshes are usually of most ecological importance in the dry season. These smaller floods stimulate spawning in fish, flush out poor quality water, mobilise sandy sediments, and contribute to flow variability. They re-set a wide spectrum of conditions in the river, triggering and synchronising activities as varied as upstream migration of fish and germination of riparian seedlings.
Large floods that occur less than once a year.	Large, scouring floods dictate the form of the channel. They mobilise sediments and deposit silt, nutrients and seeds on floodplains. They inundate backwater areas, and trigger the emergence of flying adults of aquatic insects, which provide food for fish, frogs and birds. They maintain moisture levels in the banks, which support trees and shrubs, inundate floodplains, and scour estuaries thereby maintaining the link with the sea.
Flow variability	Variability of flow is essential for a healthy ecosystem. Different conditions are created through each day and season, controlling the balance of species and preventing dominance by pest species.

Table 2.1: Effects of different components of a flow regime on aquatic ecosystems (Brown and King, 2000)

Recommendations for environmental flow requirements therefore usually specify flows of different magnitude and timing in an attempt to simulate the fundamental character encompassed in the natural flow regime. Figure 2.2 depicts the important features of a winter rainfall river's natural flow regime. Features 1 and 6 may recognize the perenniality of the river ; 2, 4 and 5 may recognize the importance of the difference between wet and dry season low flows; and 3 may recognize the timing of the first major flood of the wet season (King and Louw, 1998).

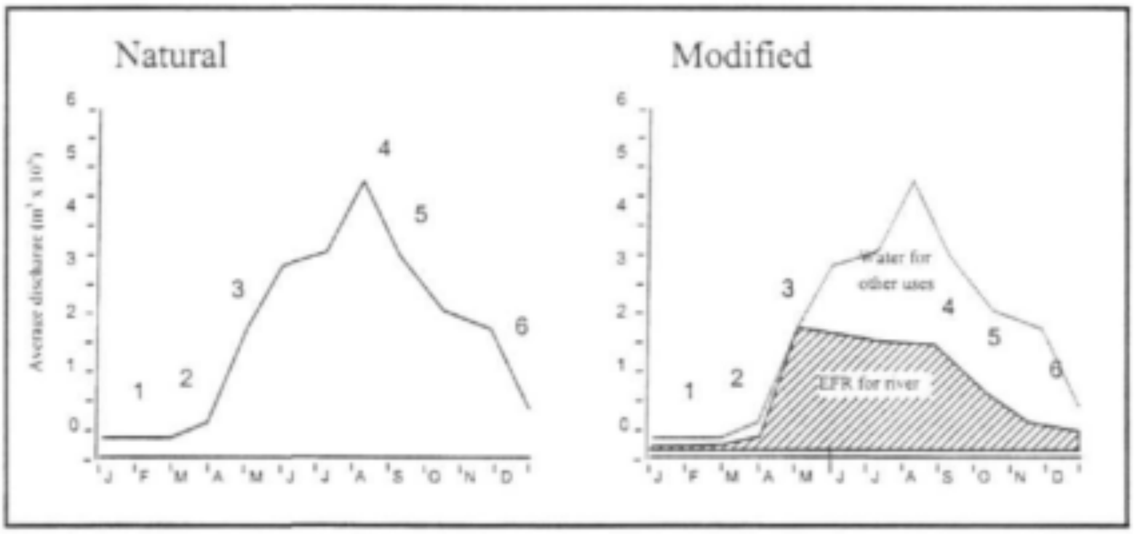


Figure 2.2 : Perceived important features of a winter rainfall river's natural flow regime (expressed as monthly averages) incorporated into the modified flow regime (King and Louw, 1998)

The main flow components comprising an EFR are:

- Low flows
- Freshes
- Channel forming flows

The low flow component maintains the basic ephemeral or perennial nature of the river and through its different magnitudes in the wet and dry seasons, creates fundamentally different seasonal conditions (King and Louw, 1998). Low flows can be further categorized into optimum, minimum and survival flows depending on the degree to which it meets the survival requirements of aquatic species. Some species may rely on low flows for a part of their life history, for others it is a time of stress (Gordon *et al.*, 1992). Short pulses of higher flows, known as freshes, trigger spawning in some fish species, mobilize sandy sediments during the wet and dry seasons, dilute poor quality waters and provide essential flow variability. Channel forming flows are necessary for re-setting a wide spectrum of conditions in the river and riparian ecosystems. It maintains the active channel form and diversity of physical biotopes and removes encroaching riparian vegetation. Depending on the magnitude of the channel forming flow it is sometimes referred to as either a channel maintenance flow or a flood, with channel maintenance flows typically of a smaller magnitude than floods. Another important flow component relevant to cobble and boulder bed rivers is the so-called flushing flow or sediment maintenance flow. This flow aims to flush fine sands and sediments from the interstitial spaces between the cobbles and gravels downstream of reservoirs, introduced into this part of the river system from the incremental catchments downstream of the reservoir.

2.3 Environmental flow assessment methods

2.3.1 Overview

Research on environmental flow requirements, suggests that the flows which represent the normal characteristics of a specific river are the ones that the riverine biota are adapted to. In other words, the full range of natural intra- and interannual variation of flow regimes, and associated characteristics of timing, duration, frequency as well as rate of change, are critical in sustaining the integrity of aquatic ecosystems (Richter *et al.*, 1997). Therefore, flows that are not characteristic to a specific river, will constitute an atypical disturbance to the riverine ecosystem and could fundamentally change its character (King and Louw, 1998).

In establishing environmental flow requirements, the difficulty lies in deciding how much modification of the natural flow regime is acceptable. The lack of quantitative data on the effects of regulated flows on organisms is a limitation, which becomes especially critical when the preservation of aquatic habitat conflicts with other uses of water. Furthermore, financial and timing constraints do not allow extensive and detailed studies on species requirements in specific reaches and rivers. Cost effective, objective and consistent techniques, which provide reliable estimates of habitat requirements, have therefore been developed and are continuously being refined. These techniques are grouped into two broad approaches, viz. prescriptive and interactive approaches.

2.3.2 Prescriptive approaches

Methods based on the prescriptive approach usually address a narrow and specific objective and result in a recommendation for a single flow value or flow regime (Brown and King, 2000). They can be divided into three categories (Tharme, 1996), viz. hydrological index methods, hydraulic rating methods and holistic approaches.

i. Hydrological index methods.

Examples of these methods are the Tennant or Montana method (Tennant, 1976) and the "Range of Variability Approach" (Richter *et al.*, 1997). These techniques recognize that hydrological variation plays a major part in structuring the biotic diversity within river ecosystems as it controls key habitat conditions within the river channel and floodplain (Richter *et al.*, 1997). They aim to maintain native aquatic biodiversity and ecosystem integrity by maintaining some semblance of natural flow variability, based on natural streamflow records. Flow requirements are either specified as a single minimum flow value or as different proportions of flow (% MAR) retained at different times of the year. The main attraction of these methods is the fact that an answer can be obtained rapidly if flow records are available, eliminating the time and cost of field data collection. However, little if any attention is given to the specific nature of the considered river or its biota (Brown and King, 2000). Furthermore, although these methods are specific about the magnitude of flow, they are vague about the timing and duration of flows and comprise no understanding or "feel" for the ecosystem (Gordon *et al.*, 1992).

ii. Hydraulic rating methods.

These methods employ the relationship between the flow of the river (discharge) and simple hydraulic characteristics calculated from field data such as water depth, velocity or wetted perimeter, to advise on acceptable flows. However, they focus more on relationships between physical features of the river than on flow-related needs of the biota (Brown and King, 2000). Cross sections are usually chosen at ecologically critical sites, such as riffles, as it is reasoned that riffles will be affected more severely by flow alterations than pools, for example.

One example of this type of method is the Idaho method (Cochnauer, 1976 ; White, 1976). It employs a backwater calculation programme for calculating hydraulic parameters (flow depth, average velocity and wetted perimeter) at each transect for different discharges, which can be compared with known biological criteria.

Another example, the Wetted-Perimeter Method (Collings, 1972), is a low-resolution, river-specific method that is useful for determining seasonal flows required to maintain fish populations. It is relatively quick and cost-effective and is useful as a planning method at a catchment or greater level (Tharme, 1996). The method is based on the assumption that fish rearing is related to food production, which in turn is related to how much of the river bed is inundated. It uses relationships between wetted perimeter and discharge, depth and velocity to set minimum discharges for fish food production and rearing (including spawning). The relationships are constructed from measuring the length of the wetted-perimeter at different discharges in the river of interest. The resulting recommended discharges are based on inflection points on the wetted-perimeter/discharge curve, each of which is assumed to represent the maximum habitat for minimum flow before the next inflection point.

iii. Early holistic approaches

These methods require collection of considerable river-specific data, and make structured links between flow characteristics of the river and the flow needs of the main biotic groups (fish, vegetation, invertebrates) (Brown and King, 2000). Examples include the Holistic Method and the Building Block Methodology.

The Holistic Method (Arthington *et al*. 1992) and the Building Block Methodology (King and Louw, 1998) were developed in parallel. The methodologies share the same basic tenets and assumptions, and both require early identification of the future desired condition of the river (Brown and King, 2000). An EFR is then described that should achieve and maintain this condition. Both involve the construction of a modified flow regime on a month-by-month basis, through separate consideration of different components of the flow regime. Each flow component represents "a well-defined feature of the flow regime intended to achieve particular ecological, geomorphological or water-quality objectives in the modified river ecosystem" (Arthington *et al*. 1992).

The Holistic Method is essentially an amalgamation of various methods and computer software, which relies heavily on expert opinion. It is used to ascertain the effects of reduced or increased flows on a river and to examine the impacts of periods of low, relatively constant flows, and of high, wet-season flows and floods, on the migration, spawning and dispersal requirements of fish (Brown and King, 2000). The Building Block Methodology (BBM) is based on the assumption that there are some flows within the total flow regime of a river that are more important than others for the maintenance of that river ecosystem. Such flows can therefore be identified in terms of their timing, duration, frequency and magnitude and combined into a recommended modified flow regime that is specific for that river. During identification of these flows, the focus is on the characteristic features of the natural flow regime of the river. As indicated in Figure 2.3, each of the identified flows is considered a building block that creates the modified flow regime or EFR and is deemed to perform a required ecological or geomorphological function (King and Louw, 1998). The BBM was designed to cope with the southern African realities of limited data, money and time. It depends on available knowledge, expert opinion and some new data, which are used in a structured workshop session to describe an EFR (King and Louw, 1998). It considers the major components of the river ecosystem, both physical (hydrology, physical habitat, and chemical water quality) and biological (vegetation, fish and macroinvertebrates), as well as subsistence use of the river by riparian people. For each of these disciplines, all available data are synthesized and new data collected where necessary. Field measurements always include the surveying of cross-sections at representative sites along the river and development of the relationship between flow and water depth, velocity and area of inundation. The biological specialists also conduct field studies from which they develop an understanding of the links between aquatic species and the flow in the river at different times. The strength of the BBM therefore lies in its ability to incorporate any relevant knowledge, and to be used in both data-rich and data-poor situations (Brown and King, 2000).

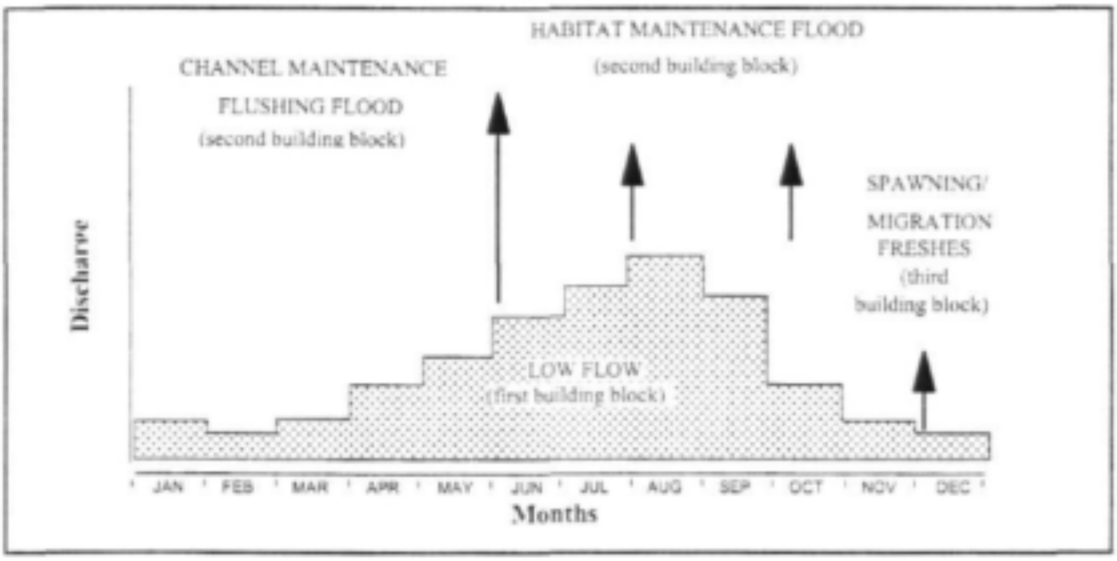


Figure 2.3 : The "building blocks" of the modified flow regime created using the BBM (King and Louw, 1998).

2.3.3 Interactive approaches

The EFA methods that use an interactive approach tend to be more complex than prescriptive methods and are predominantly limited to two types, viz. habitat simulation and holistic methodologies. Both are essentially problem-solving tools, the output of which is a set of options (Brown and King, 2000). Each option quantitatively describes :

- a modified flow regime
- the resulting condition of the river, or species (whichever is being addressed)
- the effect on yield for offstream users
- the direct economic costs and benefits

i. Habitat simulation methods

Instream habitat simulation methods can be considered to be sophisticated hydraulic rating methods. Whereas hydraulic rating methods are based on the optimum ranges of velocity and depth determined for a species, habitat simulation methods use a continuous function to describe preferences and allow more flexibility in evaluating the effects of changing discharges on habitat availability (Brown and King, 2000). Furthermore, it considers not only how physical habitat changes with discharge, but combines such information with the habitat preferences of different species. (Table 2.2, for example, lists the typical habitat requirements for various fish species.) In this way the available habitat for specific species over a range of discharges are determined.

Species	Depth (m)	Velocity (m/s)	Substrate type
Blackfish	> 0,20	0 – 0,30	All
Brown trout	> 0,20	0 – 0,50	All
Redfin/Common carp	>1,0	0 – 0,20	Mud/Sand
Short-finned eel	> 0,20	0 – 0,30	All

Table 2.2 : Hydraulic habitat requirements for rearing habitat of fishes of Southwestern Victoria (Tunbridge, 1988)

The Instream Flow Incremental Methodology (IFIM) is considered to be the most sophisticated instream habitat simulation method. IFIM was devised by the United States Fish and Wildlife Service to assist in the assessment of environmental flow requirements of rivers (Bovee, 1982). Basically, IFIM is a problem-solving tool, comprising a collection of analytical procedures and computer programs, including the physical habitat simulation model, PHABSIM II. This model simulates hydraulic conditions over a range of discharges and then links the hydraulic information with habitat information on key riverine species to produce habitat discharge relationships (Bovee and Milhous, 1978; Milhous *et al.*, 1989). It considers the effect of incremental changes in discharge on both the macrohabitat (channel characteristics, temperature and water quality) and microhabitat (distribution of hydraulic and structural features making up the living space for an organism). The two basic components of the model are hydraulic simulation and habitat simulation. Hydraulic simulation is based on measured and/or calculated data at selected cross sections and predicts conditions of velocity, water depth, substrate and hydraulic and vegetal cover over a range of discharges. Simulations are done at a level of resolution deemed to be ecologically relevant, by compartmentalizing the cross section into a grid of lateral cells extending halfway to adjacent cross sections. The hydraulic conditions in each cell are then simulated. Data are also collected on the habitat preferences of the selected riverine species. Based on the assumption that the habitat of aquatic species is determined by the hydraulic environment, habitat curves are constructed, showing species' preferences on a scale of 0 to 1 in terms of water depth, velocity, substrate and cover conditions. Typical examples of these curves, also known as "suitability index curves" or SI curves, are shown in Figure 2.4.

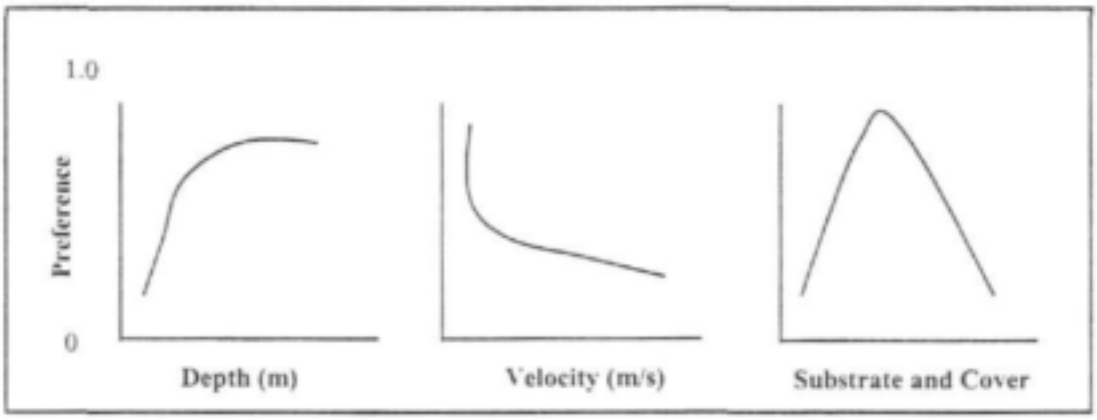


Figure 2.4 : Suitability index curves for a specific species' life stage

PHABSIM II then links the information on the hydraulic conditions within each cell with that on the preferred habitat of species, by using the SI curves to assess the suitability of hydraulic conditions at different discharges. The suitability for each cell at each discharge is then expressed as a combination of velocity, depth, substrate and cover conditions by a composite factor, known as "available flow-related microhabitat" or the "Weighted Usable Area" (WUA). WUA is therefore an indicator of the net suitability of use of a given reach by a certain life stage of a certain species and is expressed in units of area per unit length of river (Figure 2.5).

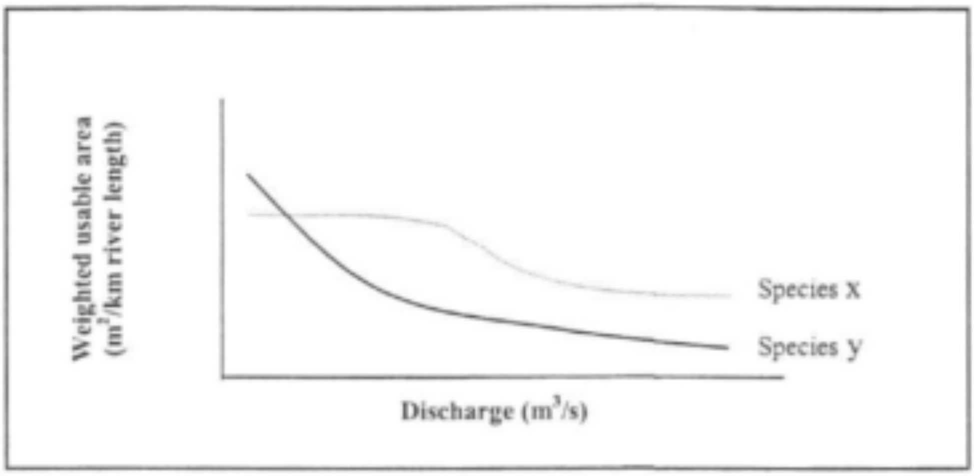


Figure 2.5 : Available habitat as a function of discharge

To extend the relevance of the PHABSIM output, the habitat-discharge functions may be combined with flow data to obtain monthly or daily habitat time series and habitat duration curves. Such curves are useful for comparing pre- and post project habitat availability.

Habitat simulation models are useful tools for determining instream flow requirements. However, some limitations have been identified. A critical limitation is the high cost of developing well-defined habitat-suitability curves. Furthermore, the curves may not be transferable from one stream to another. Another potential limitation is the inaccurate application of hydraulic calculation procedures such as backwater calculations or stage discharge relationships, due to inaccurate or insufficient cross sectional or roughness data.

ii. Holistic methodologies

Another type of interactive approach involves the so-called holistic methods, of which the DRIFT model is a typical example. DRIFT (Downstream Response to Imposed Flow Transformations) was developed for the assessment of environmental flows for the Lesotho Highlands Water Project. The methodology arose from, and its data-collection steps closely approximate those of, the BBM. Like the BBM, DRIFT culminates in one or more multidisciplinary workshops, but unlike the BBM, these are designed to produce an agreed number of biophysical and socio-economic scenarios (Brown and King, 2000). The central rationale of DRIFT is that different parts of the flow regime, e.g., low flows, freshes and floods of a river elicit different responses from the components of the riverine ecosystem. Thus, removal of one or more kinds of flow will affect the riverine ecosystem differently than removal of some other combination (Brown and King, 2000). Within DRIFT, the specialists use component-specific methods to collect data and predict the consequences of flow changes in the way required by DRIFT.

Essentially DRIFT is a system for managing a great amount of data and knowledge in a structured way, following five main steps (Brown and King, 2000) :

- Identification and isolation of wet-season and dry-season low flows, freshes, and floods from the long-term hydrological record.
- Description of the consequences for the river of partial or whole removal of each of these flow components.
- Creation of a biophysical database detailing the consequences.
- Use of the database to describe how river conditions will change with any future combination of high and low flows removed.
- Description of the socio-economic implications of changes in river condition. (This and the previous step constitute the creation of EFR scenarios.)

Figure 2.6 is a diagrammatic representation of the DRIFT methodology.

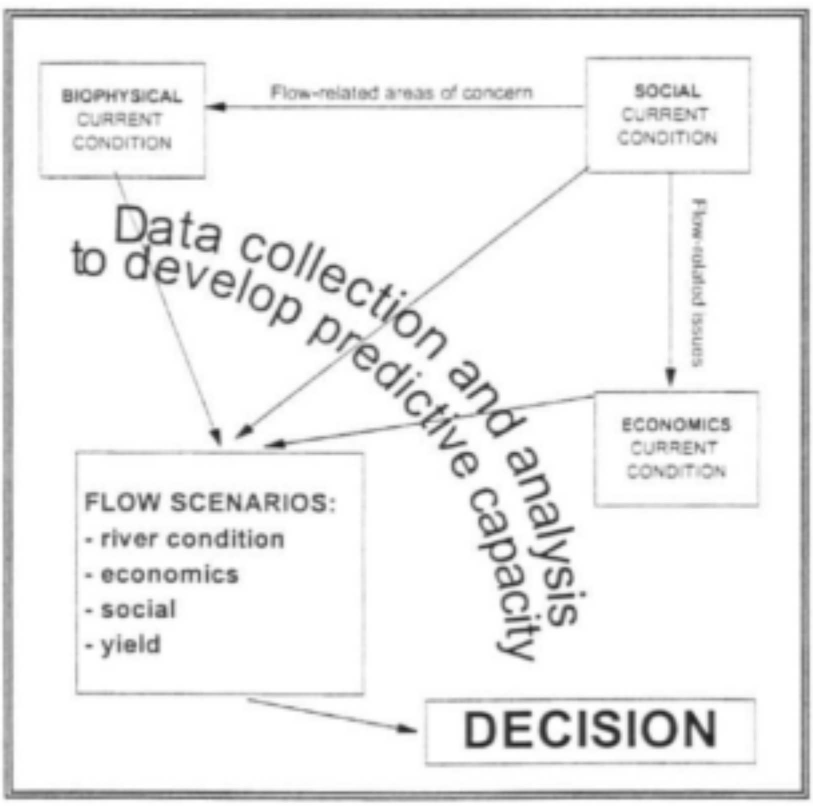


Figure 2.6 : Basic components of a DRIFT assessment (Brown and King, 2000)

The DRIFT methodology can also be used for advising on flow restoration for degraded rivers, by describing the consequences of adding rather than removing flow components (King, pers. comm., 2001)

2.4 Environmental flow assessment in South Africa

Currently, the Department of Water Affairs and Forestry (DWAF) applies the procedure of Integrated Environmental Management for any proposed water resources development. During this procedure, after the original Reconnaissance Phase, which often takes the form of a catchment study or regional water resources systems analysis, the most probable options are identified. During the following Pre-Feasibility Phase, these options are further investigated. This is done in conjunction with an environmental impact assessment of the different options, known as the Relevant Environmental Impact Prognosis (ROIP). As part of the ROIP, a workshop is held to describe the expected change in flow regime and the consequences thereof and to ultimately propose an EFR.

2.5 Conclusion

As is evident from the above, various methodologies and approaches, representing different levels of detail across different spatial scales, have been developed for determining the quantity of water which is required for the environmental needs of a river. These techniques are motivated by the conviction that it is the hydraulic conditions, which are determined by the interaction between the moving water and the physical attributes of the river channel, that determine ecosystem functioning through the availability of physical habitat for aquatic species. The essence of these techniques, therefore, is to anticipate the effect of a modified flow regime on the morphological and associated hydraulic characteristics of a river. In order to achieve this, certain "tools" are required which serve to predict changes in channel morphology and hydraulic conditions, at both the reach and the local scale, for different flow regimes. Consequently, this study focuses on the development of empirical, semi-empirical, theoretically-based and statistical models aimed at addressing key components in the assessment of environmental flow requirements in cobble and boulder bed rivers, viz. macro scale bed deformation, the scouring of sand from the interstitial spaces between the cobbles, stage discharge relationships under conditions of large scale roughness as well as the probability distribution of local flow velocities.

3. INTRODUCTION TO RIVER HYDRAULICS CONCEPTS

3.1 Introduction

River hydraulics involves the description by either numerical, analytical or experimental methods, of the characteristics of flow in river channels. There are generally three different bases for such a description. The first is the process of theoretical analyses based on the fundamental principles of fluid dynamics. A second is the method of experimental analysis on hydraulic scale models in the laboratory. Finally there is the method of "engineering experience" gained by individuals involved in the field of river hydraulics. The most effective solution of many river hydraulics problems involves a combination of these three methods.

This chapter aims to provide river scientists and ecologists with an introduction to the science of river hydraulics and focuses on the basic hydraulic concepts applied in this report. It addresses the classification of open channel flow as well as the fundamental principles describing open channel flow, the concepts of uniform flow and flow resistance and finally, basic sediment transport theory. Scientists from a biological or geomorphological background are referred to the following "non-technical" text books, for additional reading on open-channel hydraulics: Valentine (1967); Kay (1998); Gordon *et al*. (1992).

3.2 The classification of open channel flow

Flow of a liquid with a free surface, known as open channel flow, is in general much more complicated than flow in pipes and other closed conduits. The free surface is subjected only to atmospheric pressure and, since this pressure is constant, the driving force is the weight component of the fluid. Open channel flow can be described in various ways. However, it is mainly classified according to the type of flow and the state of flow. Flow classification according to type relates to the change in flow depth with respect to time and space, whereas the state of flow relates to the behaviour of the flow as a result of gravity-, viscosity- and inertial forces.

3.2.1 Flow type

i. Time : Steady and Unsteady flow

Flow is termed steady or unsteady according to whether the velocity and flow depth at a particular point in the channel varies with time. In most problems concerned with open channels, the flow is deemed to be steady, i.e. the velocity and depth at a fixed point does not vary with time. However, strongly unsteady flow does occasionally occur, for example surge waves during floods.

ii. Space : Uniform and Varied flow

Flow is uniform if the velocity and the flow depth do not change, either in magnitude or direction, from one section to another. This condition is achieved only if the cross section does not change along the length of the channel. Uniform flow is characterised by the liquid surface being parallel to the bed of the channel. Flow in which the liquid surface is not parallel to the bed of the channel is said to be non-uniform or varied, in other words the depth and velocity of flow varies along the length of the channel. Varied flow may be further classified as either gradually or rapidly varied. If the flow depth changes abruptly over a relatively short distance, it is termed rapidly varied. Otherwise, it is termed gradually varied.

3.2.2 The state of flow

i. Viscosity effects

The effect of viscosity relative to inertia determines whether the flow is laminar or turbulent. Laminar flow prevails if the viscous forces are so strong relative to the inertial forces, that flow behaviour is influenced significantly by the viscous forces. The water particles move as thin layers of fluid sliding over adjacent layers. In the case of turbulent flow the viscous forces are weak relative to the inertial forces and the water particles move in irregular paths as instantaneous eddies. In channels of engineering interest, laminar flow very rarely occurs and turbulent flow may invariably be assumed.

The effect of viscosity relative to inertia, is represented by the **Reynolds number,** defined as :

$$R_e = \frac{vy}{\nu} \tag{3.1}$$

with v : flow velocity (m/s)

y : flow depth (m)

ν : kinematic viscosity of water (m^2/s)

Open channel flow is laminar if the Reynolds number is small, less than about 600 (Massey, 1989), and turbulent if its value is more than about 4000 - although there is actually no definite upper value (Chow, 1959). Between the laminar and turbulent states, there is a transitional state.

ii. Gravity effects

The relative magnitude of inertial forces to gravity forces, is represented by the **Froude number:**

$$Fr = \frac{v}{\sqrt{gy}} \qquad (3.2)$$

with g : gravitational acceleration (m/s^2).

Based on the value of the Froude number, flow can be either subcritical, supercritical or critical. If the gravity forces are dominant relative to the inertial forces, the flow is subcritical (also described as tranquil) and the value of the Froude number is less than one. On the other hand, a Froude number greater than unity represents supercritical flow (also termed rapid or shooting flow). In this state the inertial forces are strong relative to the gravity forces and the flow has a high velocity. In order for flow to change from sub- to supercritical, it must pass through the critical state where the Froude number equals one. When flow changes from supercritical to subcritical it is associated with high energy losses in the form of a standing wave, commonly referred to as a hydraulic jump. An important difference between sub- and supercritical flow is the ability of a small gravity wave, caused as a result of a disturbance to the local depth of the water, to propagate upstream. Under subcritical conditions, the wave can travel against the flow and affect conditions upstream, while the wave is washed downstream under supercritical conditions.

A complete description of the flow in an open channel can therefore be summarized as a combination of various characteristics. Open channel flow is either:

- Uniform or Varied
- Steady or Unsteady
- Laminar, Transitional or Turbulent
- Subcritical, Supercritical or Critical

3.3 Fundamental principles of open channel flow

In flow analysis, three fundamental laws are normally used in combination. These are the laws of conservation of mass, momentum and energy and are respectively represented by the continuity, momentum and Bernoulli equations. (An additional basic principle useful for describing flow relationships, is the law of conservation of power. However, this principle is related mathematically to the laws of conservation of momentum and energy and is not considered an independent law (Rooseboom, 1994)).

3.3.1 The principle of conservation of mass (Continuity equation)

Consider a fixed space within a fluid. Since matter is neither created nor destroyed within the space, it means that:

Rate at which mass enters = Rate at which mass leaves + Rate of accumulation of mass.

Under steady state conditions, the rate of mass accumulation within the region is zero and therefore:

Rate at which mass enters the region = Rate at which mass leaves the region.

Applying this expression to an incompressible fluid, reads:

$$\Sigma \textit{Inflows into fixed region } (\Sigma Q_{in}) = \Sigma \textit{Outflows from fixed region } (\Sigma Q_{out})$$

For open channel flow, the discharge through a cross section perpendicular to the direction of flow, is expressed by

$$Q = V\,A \qquad (3.3)$$

where Q is the discharge, V is the mean velocity and A is the flow cross sectional area. Under steady flow conditions, therefore, the continuity equation applied to open channel flow states that

$$Q = V_1A_1 = V_2A_2 = \ldots \qquad (3.4)$$

where the subscripts 1 and 2 denote different cross sections.

3.3.2 The principle of conservation of momentum (Momentum equation)

In its general form, Newton's Second Law states that the net force acting on a body in any fixed direction is equal to the rate of increase of momentum of the body in that direction. Applying this law to a body of fluid in an open channel, leads to the momentum equation and reads (for a given direction):

Sum of external forces acting upon fluid = Change of momentum per unit time in fluid

The momentum of the flow passing a channel section per unit time is expressed by:

$$\beta\rho QV \tag{3.5}$$

with β : momentum correction factor

ρ : density of water (kg/m^3)

Q : discharge (m^3/s)

V : average velocity over cross section (m/s)

Therefore, if the momentum equation is applied to a body of water in an open channel of slope θ, the following equation results:

$$\sum\beta\rho QV_{(out)} - \sum\beta\rho QV_{(in)} = P_1 - P_2 + w\sin\theta - F_f \tag{3.6}$$

with P_1 : water pressure force at upstream section (N)

P_2 : water pressure force at downstream section (N)

w : weight of water (N)

F_f : external frictional force exerted by boundaries (N)

The momentum equation is the only vectorial equation among the three fundamental equations and it is therefore essential that the correct components of the various forces and momentum fluxes are introduced into the equation. It is also the only equation which can be used for the analysis of forces in fluid flow.

3.3.3 The principle of conservation of energy (Energy equation)

In open channel hydraulics, the total energy per unit weight of a water element which passes through a cross section is expressed as the total head in metres of water, which is the sum total of the elevation of the element above a datum, the pressure head and the velocity head. Thus the total head (energy) at a cross section in a channel with slope θ, is

$$H = z + y\cos\theta + \alpha\frac{V^2}{2g} \tag{3.7}$$

with H : total head (m)

z : bed elevation above datum (m)

y : water depth perpendicular to bed (m)

α : energy correction factor

V : average velocity over cross section (m/s)

Based on the law of conservation of energy, the total head at an upstream cross section (denoted by subscript 1) is equal to the total head at the downstream cross section (subscript 2) plus the energy losses encountered between the two sections (refer to Figure 3.1). Therefore

$$z_1 + y_1 \cos\theta + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 \cos\theta + \alpha_2 \frac{V_2^2}{2g} + h_f + h_l \qquad (3.8)$$

with h_f : friction loss between sections 1 and 2 (m)

h_l : transition loss between sections 1 and 2 (m)

Friction losses are associated with the internal dissipation of energy due to mechanical energy being converted into heat and thus being lost. Transition losses, on the other hand, are associated with a change in velocity, e.g. at divergent or convergent sections or at bends. The energy being used is provided through a steady decrease in potential energy content of the stream.

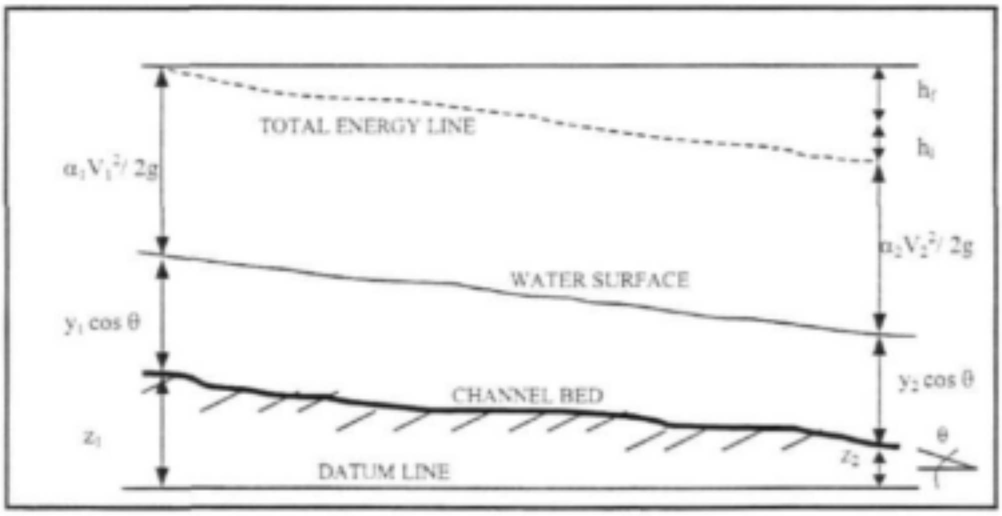


Figure 3.1 : The energy principle

3.4 Flow resistance and uniform flow

When flow occurs in an open channel, resistance is encountered by the water as it flows downstream. This resistive force is generally counteracted by the gravity force component acting on the water body in the direction of flow. The magnitude of the resistive force is directly related to the flow velocity. If water enters a channel slowly, the velocity and hence the resistance are small. The resistance is therefore less than the gravity force component with a resulting acceleration in flow. The velocity and resistance gradually increase until the forces are balanced. At this moment the flow becomes steady.

As mentioned in paragraph 3.2.1, uniform flow is characterized by a constant depth, water area and flow velocity over the length of the channel. Another characteristic feature is the parallel water surface and channel gradient. This type of flow is only established in long, straight channel reaches with a constant cross section and channel roughness. In such reaches, the flow depth is only dependent on the local channel slope, roughness and cross section and is often called the "normal" depth. In natural streams, strictly uniform flow is rarely experienced. However, uniform flow is frequently assumed as it allows for relatively simple analysis of complex flow patterns.

The estimation of the average velocity under conditions of uniform flow is in essence related to the flow resistance. The general form of equations which relate the mean velocity of steady uniform flow in open channels to flow resistance, is as follows:

$$V = cR^{x_a} s^{x_b} \tag{3.9}$$

with V : average velocity

c : resistance coefficient

R : hydraulic radius

s : energy gradient ≈ channel gradient

x_a, x_b : constants

Various forms of this relationship have been developed, based on a variety of empirical, semi-empirical and theoretical considerations. The most common of these are the Manning and Chézy equations, which are essentially empirical in nature, and the Darcy Weisbach equation, which is partially based on theoretical boundary layer considerations:

Chézy :

$$V = C\sqrt{Rs} \tag{3.10}$$

Manning : $$V = \frac{1}{n} R^{2/3} s^{1/2} \tag{3.11}$$

Darcy-Weisbach : $$V = \sqrt{\frac{8g}{f}} \sqrt{Rs} \tag{3.12}$$

C, *n* and *f* in the above equations, are "resistance coefficients", which depend upon various factors, viz. surface roughness, vegetation, channel irregularities and alignment, silting and scouring, channel size and shape, obstruction to flow and flow depth (Chow, 1959). The greatest difficulty in applying these formulae therefore lies in the determination of the appropriate roughness coefficient, which reflects the resistance to flow.

3.5 Basic sediment transport theory

Understanding the sediment transport processes in rivers is a prerequisite for describing both the long term geomorphological character of rivers as well as the short term changes to channel form and equilibrium behaviour. The mathematical description of sediment motion in rivers is mainly concerned with two phases, viz. the initiation of particle movement and the actual transport of sediment particles.

3.5.1 The initiation of movement

The prediction of sediment entrainment is usually based on some "critical" state above which particles begin to move. This "threshold" condition can be defined in different ways. One method is to model lift and drag forces on sediment particles. However, because of the fluctuating upward velocity components of turbulent flow, these forces are very difficult to model under turbulent flow conditions. Another approach involves the definition of a critical velocity based on experimental data, above which erosion is initiated (Hjulström, 1939). The third method, which is the most widely used method for describing the initiation of movement of sediment particles, is based on the concept that a critical shear stress is required to set a particle into motion. It is assumed that at the threshold condition, the shear force acting on a particle is balanced by the submerged weight of the particle. By equating these forces, an equation for critical shear stress can be obtained, viz.

$$\tau_c = \theta_c g d(\rho_s - \rho) \tag{3.13}$$

with τ_c : critical shear stress (N/m^2)

θ_c : dimensionless parameter

d : particle diameter (m)

ρ_s : particle density (kg/m^3)

ρ : water density (kg/m^3)

From experimental data, Shields (1936) related θ_c to another dimensionless factor, termed the "roughness Reynolds number" (Re^*) as shown in Figure 3.2, which depicts threshold flow conditions. The roughness Reynolds number is defined as

$$R_e^* = \frac{V^* d}{\nu} \tag{3.14}$$

with V^* : shear velocity ≈ $\sqrt{gys}$ (m/s)

(The value of Re^* gives and indication of whether the flow is considered hydraulically rough ($Re^* > 40$) or hydraulically smooth ($Re^* < 1.5$), with a transition zone in between.)

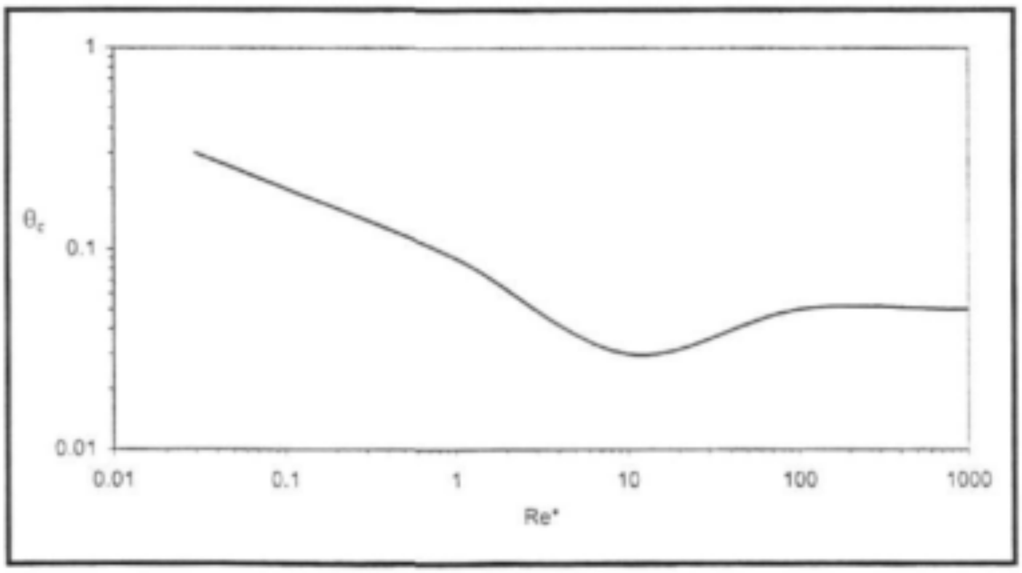


Figure 3.2 : Shields diagram

The principle of minimum applied stream power has also been used to define the threshold condition for sediment movement (Rooseboom, 1974; 1998). The approach is based on the concept that where alternative modes of flow exist, that mode of flow which requires the least amount of unit power will be followed. It therefore follows that fluid flowing over movable material will begin to transport the material, if it will result in a decrease in the amount of unit power being applied. From experimental data, Rooseboom calibrated equations defining critical conditions for sediment movement under both laminar and turbulent boundary conditions.

3.5.2 Sediment transport

In practice, virtually all sediment transport in rivers occur as either bed load, or as a combination of bed and suspended load, also referred to as total load. Several sediment transport equations have been developed. Equations describing the transport of bed load are either empirical, or derived through sophisticated statistical analyses. These formulae are often similar and can be divided into three groups displaying similar type equations, viz. Du Boys type equations, Schoklitsch-type equations and Einstein-type equations (Graf, 1971). Equations describing the suspended load or total load of sediment being transported in rivers are often very complex. Typical examples of suspended load equations are Rouse's distribution equation (Rouse, 1937), Lane and Kalinske's approximate method (Lane and Kalinske, 1939) and empirical equations (e.g. Engelund, 1970). Examples of total load equations include the Ackers and White formula (Ackers and White, 1973) and Graf's method (Graf, 1984). When applying these equations it is important to be aware that their results differ appreciably and should only be considered as estimates.

4. CHANNEL MORPHOLOGY : AN OVERVIEW

4.1 Introduction

Channel morphology (also referred to as fluvial geomorphology) is the branch of science that attempts to find systematic order in the wide array of landforms shaped by rivers and tries to understand the processes responsible for their development (Kellerhals and Church, 1989). The interaction between the moving water and the physical attributes of a river, as described by channel morphology, determines ecosystem functioning through the availability of physical (hydraulic) habitat for aquatic species. An understanding of the basic morphological concepts is therefore imperative when assessing environmental flow requirements, especially in the case of cobble and boulder bed rivers, which are characterized by macro bed forms and which, due to their characteristic morphological and associated hydrological attributes, display extreme habitat diversity.

This chapter describes the basic concepts related to fluvial geomorphology in terms of channel type, location within the longitudinal profile, channel pattern and channel structure, and provides a framework for the morphological classification of cobble and boulder bed rivers in the Western Cape.

4.2 Channel type

River channels can be classified into two broad types, viz. bedrock and alluvial channels. Richards (1987) defined bedrock channels as "channel segments which lack a coherent bed of active alluvium". In bedrock channels the geology of the channel bed and its resistance to erosion are the main determinants of channel form (Rowntree and Wadeson, 1999). The gradient of bedrock channels therefore exhibits no necessary correlation with discharge and sediment characteristics. Bedrock sections are common along many rivers in mountainous regions, often occurring as short riffles or waterfalls, but most commonly form the headwater tributaries in otherwise alluvial channels (Richards, 1987).

As opposed to bedrock channels, alluvial channels are defined as channels that flow through sediments which they have previously deposited, with the form of the channel being a result of the balance between the available sediment and the transport capacity of the river. Alluvial channels are free to adjust their dimensions and as a result consistent relationships exist between discharge and channel width, depth and gradient. In alluvial rivers substrate characteristics are most commonly described in terms of substrate size. Table 4.1 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.)

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

Table 4.1:Grade scales for substrate particle size (Adapted from Brakensiek *et al.*, 1979)

Other characteristics of the substrate include the particle shape, which is typically described in terms of roundness and sphericity, while the arrangement and associated bulk properties of the substrate are described in terms of orientation, stability, porosity, density and degree of embeddedness.

Channels which display a mixture of bedrock and alluvial sediments are known as mixed bed channels.

4.3 Longitudinal zonation

Longitudinal river zones provide a basis for within-river classification that can not only be used to identify geomorphologically similar streams, but also to retain the concept of longitudinal downstream changes (King and Schael, 2001). Various geomorphological classification systems, which are based on the concept of different zones along the length of a river, have been developed. They categorize river systems in terms of gradient (Davis, 1890), sediment production and mobility (Schumm, 1977) and substrate characteristics (Pickup, 1984). Rowntree and Wadeson (1999) described the geomorphological zonation of South African rivers in terms of average channel gradient and characteristic morphological features. Table 4.2, which was originally produced by Rowntree (1996) but has been modified by King and Schael (2001) to comply with the stream types suggested by Rosgen (1994), shows the geomorphological zonation of South African rivers associated with "normal" profiles with a characteristic concave shape. (Additional zones are associated with a "rejuvenated profile", which exhibits steepening in its downstream segments.)

4.4 Channel patterns

Channel pattern classification refers to the planimetric form of the river. Generally, channel patterns can be classified into two broad categories, viz. single-thread and multi-thread channels.

Single-thread channels may further be classified into straight or meandering channels. Straight and meandering channels are discerned based on the degree of sinuosity, defined as the length of the active (thalweg) channel divided by the valley distance (Richards, 1982). Straight channels display a sinuosity of 1, while meandering channels are defined by a sinuosity of 1,5 or more. Channels with a sinuosity index of between 1 and 1,5 are referred to as sinuous. 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 characterized by multi-thread channels separated by stable islands.

4.5 Channel structure : the morphological unit

Fluvial geomorphologists have developed the concept of the morphological unit to describe elements of channel morphology. The morphological unit is the basic structure or building block comprising the channel morphology and may be either an erosional or depositional feature. Although, in the long term, its characteristics are dependent on the imposed flow regime, which determines the erosion and sediment transport processes, in the short term it is considered a constant feature (Rowntree and Wadeson, 1996). In alluvial channels, morphological units can be divided into two groups, viz. pools and bars. Pools are scour features which form upstream of hydraulic controls and which contain relatively slow flow and deep water at low flows. Bars, on the other hand, are depositional features, which can be classified according to the nature of the material composing them and by their location within the channel. Bars serve as energy dissipators that permit stable channel configurations to be maintained in the presence of sediment transport (Hey *et al.*, 1982). Table 4.3 provides a comprehensive list of morphological units associated with alluvial rivers.

Zone	Channel gradient (%)	Characteristic channel features
Source	Not specified	Low gradient, upland plateau or upland basin able to store water. Spongy or peat hydromorphic soils.
Mountain headwater	> 10	Very steep gradient stream dominated by vertical flow over bedrock with waterfalls and plunge pools. Normally first or second order streams. Reach types include bedrock fall and cascades
Mountain	4 – 9	Steep gradient stream dominated by bedrock and boulders, locally cobble or coarse gravels in pools. Reach types include cascade, bedrock fall, step-pool.
Mountain (Transitional)	2 – 4	Moderately steep stream dominated by bedrock or boulder. Reach types include plane bed, pool-rapid or pool-riffle. Confines or semi-confined valley floor with limited flood plain development.
Upper Foothills	0.5 - 2	Moderately steep, cobble bed or mixed bedrock-cobble bed channel, with plain bed, pool-riffle, or pool-rapid reach types. Length of pools and riffles/ rapids similar. Narrow flood plain of sand, gravel or cobble often present
Lower Foothills	0.1 – 0.5	Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may be bedrock controlled. Reach types typically include pool-riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present.
Lowland river	0.01 – 0.1	Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering pattern within a distinct flood plain develops in unconfined reaches where there is an increased silt content in bed or banks

Table 4.2 : Geomorphological zonation of South African river channels (King and Schael, 2001)

Morphological unit	Description
Pool	Topographical low point in an alluvial channel caused by scour, characterized by relatively finer bed material
Backwater	Detached side channel ; connected at lower end to main flow channel
Rip channel	High flow distributary channel on the inside of point bars or lateral bars; may form backwater at low flows
Plane bed	Topographically uniform bed formed in coarse alluvium, lacking well defined scour or depositional features
Lateral bar / side bar	Accumulation of sediment attached to channel margins, often alternating from one side to the other inducing a sinuous thalweg channel
Point bar	Formed on the inside of meander bends in association with pools. Lateral growth into the channel is associated with erosion on the opposite bank and migration of meander loops across the flood plain
Transverse bar	Bar forms across entire channel at an angle to the main flow direction
Riffle	Transverse bar formed of gravel or cobble, commonly separating pools
Rapid	Steep transverse bar formed from boulders
Step	Step-like features formed by large clasts (cobble and boulder) organized into discrete channel spanning accumulations ; steep gradient
Channel junction bar	Forms immediately downstream of a tributary junction due to the input of coarse material into a lower gradient channel
Lee bar	Accumulation of sediment in the lee of a flow obstruction
Mid-channel bar	Single bar formed within the middle of the channel, with strong flow on either side
Braid bar	Multiple mid-channel bars forming a complex system of diverging and converging thalweg channels
Sand waves / Lingoid bar	Large mobile feature formed in sand bed rivers which has a steep front edge spanning the channel and which extends for some distance upstream. Surface composed of smaller mobile dunes
Bench	Narrow terrace-like feature formed at edge of active channel abutting on to macro-channel bank
Islands	Mid-channel bars which have become stabilized due to vegetation growth and which are submerged at high flows due to flooding

Table 4.3 : Classification of alluvial morphological units (Rowntree and Wadeson, 1999)

Because cobble and boulder bed rivers are dominated by large clasts (detrital material consisting of fragments of broken rocks which have been eroded, transported and redeposited at a different site), which require high thresholds of stream power before movement takes place, the larger cobbles and boulders provide relatively immobile channel structures through which finer material is transported. Cobble and boulder bed rivers therefore frequently have a wide particle size range and are poorly sorted (Rowntree and Wadeson, 1999), but may be locally well sorted (King, pers. comm., 2001). The dominant bar types which occur in these reaches are transverse bars, characterized by coarse sediments, and point or alternate bars, especially in the lower reaches during low flows or when a high concentration of fine sediment is present.

4.6 Reach classification

Within a geomorphological context, Rowntree and Wadeson (1999) defined a reach as "a length of channel within which the local constraints on channel form are uniform, resulting in a characteristic channel pattern, degree of incision and cross section form within which a characteristic assemblage of channel morphologies occur." Reaches in cobble and boulder bed rivers, which are classified as alluvial rivers, may be classified based on their assemblage of morphological units (Table 4.4).

Reach type	**Description**
Step-pool	Characterized by large clasts which are organized into discrete channel spanning accumulations that form a series of steps separating pools containing finer material
Plane bed	Characterized by plane bed morphologies in cobble bed or small boulder channels lacking well defined scour or depositional morphological units
Pool-riffle	Characterized by an undulating bed that defines a sequence of bars (riffles) and pools
Pool-rapid	Channels are characterized by long pools backed up behind fixed boulder deposists forming rapids

Table 4.4 : Reach types in cobble and boulder bed rivers (Adapted from Grant *et al.*, 1990; Montgomery & Buffington, 1993 and Van Niekerk *et al.*, 1995)

The most common reach types associated with cobble and boulder bed rivers are the step-pool, plane bed, pool-rapid and pool-riffle.

4.6.1 Step-Pool

Step-pool reaches are characterized by large clasts organized into discrete channel spanning accumulations that form a series of steps separating scour pools containing finer material (Grant *et al.*, 1990). The channel width is of the same order of magnitude as that of the clasts themselves. There is a strong vertical component to the flow in step-pool reaches, contrasted to the more lateral flow in lower gradient pool-riffle reaches (Rowntree and Wadeson, 1999). The largest volume of sediment transported through this reach type is in the sand size (Leopold, 1992), with boulder and cobble fractions making up the major features of channel morphology, which remains stable except in rare flood events (Rowntree and Wadeson, 1999).

Figure 4.1 : A typical step-pool reach type

4.6.2 Plane bed

Another reach type commonly associated with cobble and boulder bed rivers is the plane bed, which describes channels developed in coarse bed material which lack well-defined bedform (Montgomery and Buffington, 1993). These features are quite distinct from both step-pool and pool-riffle channels in that they lack rhythmic bedforms. They appear to occur naturally at gradients and relative roughness intermediate between step-pool and pool-riffle reaches. The larger clasts are generally scattered over the channel bed and at low to moderate flows project out of the water (Wadeson and Rowntree, 1999).

Figure 4.2 : Plane bed morphological unit

4.6.3 Pool-Riffle

The alternating pool-riffle bedform is most common on streams with bed materials ranging from "pea" to "watermelon" size (Knighton, 1984). In South Africa they are dominated by substrate in the size class of cobbles and boulders (Rowntree and Wadeson, 1999). Riffles are topographic highs and are formed by the accumulation of coarse material to form a transverse bar with a steeper gradient (Selby, 1985). Pools are topographic lows, which are scour features located between riffles. Their position is often coincident with point bars situated on meander bends. The pool-riffle bedform is considered a means of self-adjustment by streams which acts to regulate energy expenditure. They are usually formed during large floods (Gordon *et al.*, 1992).

Pools and riffles are easily distinguished at low flows. However, various techniques have been developed for their objective classification. These include bed material size (Leopold *et al.*, 1964; Mosley, 1982), water surface slope (Yang, 1971; Jowett, 1993), the ratio of average velocity to average depth (Wolman, 1955; Jowett, 1993), Froude number (Jowett, 1993) and bed topography (O'Neill and Abrahams, 1984). At low discharges flow through pools is deep relative to that over riffles and the surface water gradient and flow velocity is low. Pools are therefore areas of deposition of fine material during low flow periods. Riffles, on the other hand, are characterized by coarser material and fast, shallow flow with a high velocity and surface water gradient relative to the pool.

Figure 4.3 : An example of a pool-riffle reach type

4.6.4 Pool-Rapid

This reach type is very similar to pool-riffle reaches, except that it occurs at relatively higher channel gradients and is associated mainly with boulders instead of cobbles. The rapids are characterized by highly turbulent flows and high flow velocities.

Figure 4.4 : Rapid morphological unit

II. ENVIRONMENTALLY SIGNIFICANT MORPHOLOGICAL CHARACTERISTICS OF COBBLE AND BOULDER BED RIVERS IN THE WESTERN CAPE

5. REGIME BEHAVIOUR OF COBBLE AND BOULDER BED RIVERS

5.1 Introduction

A characteristic morphological feature of cobble and boulder bed rivers is the presence of macro scale bed forms, e.g. pools, rapids and riffles and the general absence of smaller scale bed forms which may include ripples, dunes, etc. Due to the presence of these bed forms and their associated hydraulic attributes, the physical habitat associated with cobble and boulder bed rivers is extremely diverse, both on a spatial and temporal scale. The high gradient of rapids and riffles leads to turbulence and high oxygen levels, while deeper pools are associated with lower water temperatures and lower velocities. Gordon *et al.* (1992) state that "in terms of physical habitat, the pool-riffle structure provides a great diversity of bed forms, substrate materials and local velocities". This is echoed by Scheuerlein (1999) who, referring to cobble and boulder bed rivers, states that "a high variation of abiotic patterns e.g. channel width, flow depth, flow velocity, turbulence, bed structure, etc., provides the basis for valuable ecosystems". Maintaining the morphological character of cobble and boulder bed rivers is therefore an important prerequisite for sustainable ecosystem functioning.

Cobble and boulder bed rivers are classified as alluvial rivers and the concept of a regime channel applies, i.e. a self-formed channel which, when subject 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 (Richards, 1987). In order to predict the long term, morphological impacts associated with a modified flow regime on cobble and boulder bed rivers, the regime behaviour of these rivers need to be addressed and specifically the process of macro scale bed deformation.

This part of the research therefore aims to define fundamental, theoretically-based relationships between discharge, channel- and bed form geometry and substrate characteristics in a cobble and boulder bed river. Section 5.2 describes the typical morphological characteristics of cobble and boulder bed rivers in the Western Cape, while section 5.3 addresses the prediction of their regime behaviour and associated morphological characteristics.

5.2 Morphological characteristics of cobble and boulder bed rivers in the Western Cape

5.2.1 Overview

Based on field observations it was found that, in terms of general morphological characteristics, rivers in the Western Cape can be classified into two broad categories viz. the steep, coastal rivers and the typical longitudinal concave-shaped, alluvial or mixed bed rivers. Steep coastal rivers are characterized by bedrock and boulders and contain a series of waterfalls and scour pools. The channel gradient is steep and fairly constant from estuary to source. Examples of these rivers are the Rooiels and Steenbras Rivers. Alluvial or mixed bed, concave-shaped rivers, typically rise in the mountainous areas from where they flow through foothills and low-lying areas until eventually reaching either the Atlantic or Indian oceans. The upper part of the mountain zone is dominated by bedrock and boulders and is characterized by waterfalls and deep pools. Further downstream, in the mountain transitional and upper foothill zones, reaches display a step-pool, plane bed or pool-rapid morphology, dominated by boulders. Progressing down into the foothill zones, grain sizes decrease to within the range of cobbles and pool-riffle reach types start to dominate. Still further downstream, the substrate changes to gravel, sand and eventually to silt, while the channel follows a meandering pattern. Examples of these rivers within the study area are the Berg-, Breede- and Jonkershoek Rivers (refer to Figure 5.1).

5.2.2 Data collection

In order to determine the morphological character of cobble and boulder bed rivers in the Western Cape, extensive field data were collected in the cobble and boulder bed reaches which dominate in the mountain and foothill zones of the concave shaped, alluvial rivers within the study area. Thirteen study reaches were selected, representing a range of reach types in terms of substrate size, morphological structure and position within the longitudinal profile. Reach lengths typically varied from about 60 m along the upper reaches to more than 250 m along the lower reaches with each reach including at least one sequence of pool-rapid or pool-riffle structures. Table 5.1 lists the study reaches together with general, descriptive information. The definitions as provided in the previous chapter were used to assign each study reach to a reach type and longitudinal zone. Similarly, the identification of the dominant substrate class within each study reach was based on the definitions as per Chapter 4. (Appendix B displays a photograph of each study reach.)

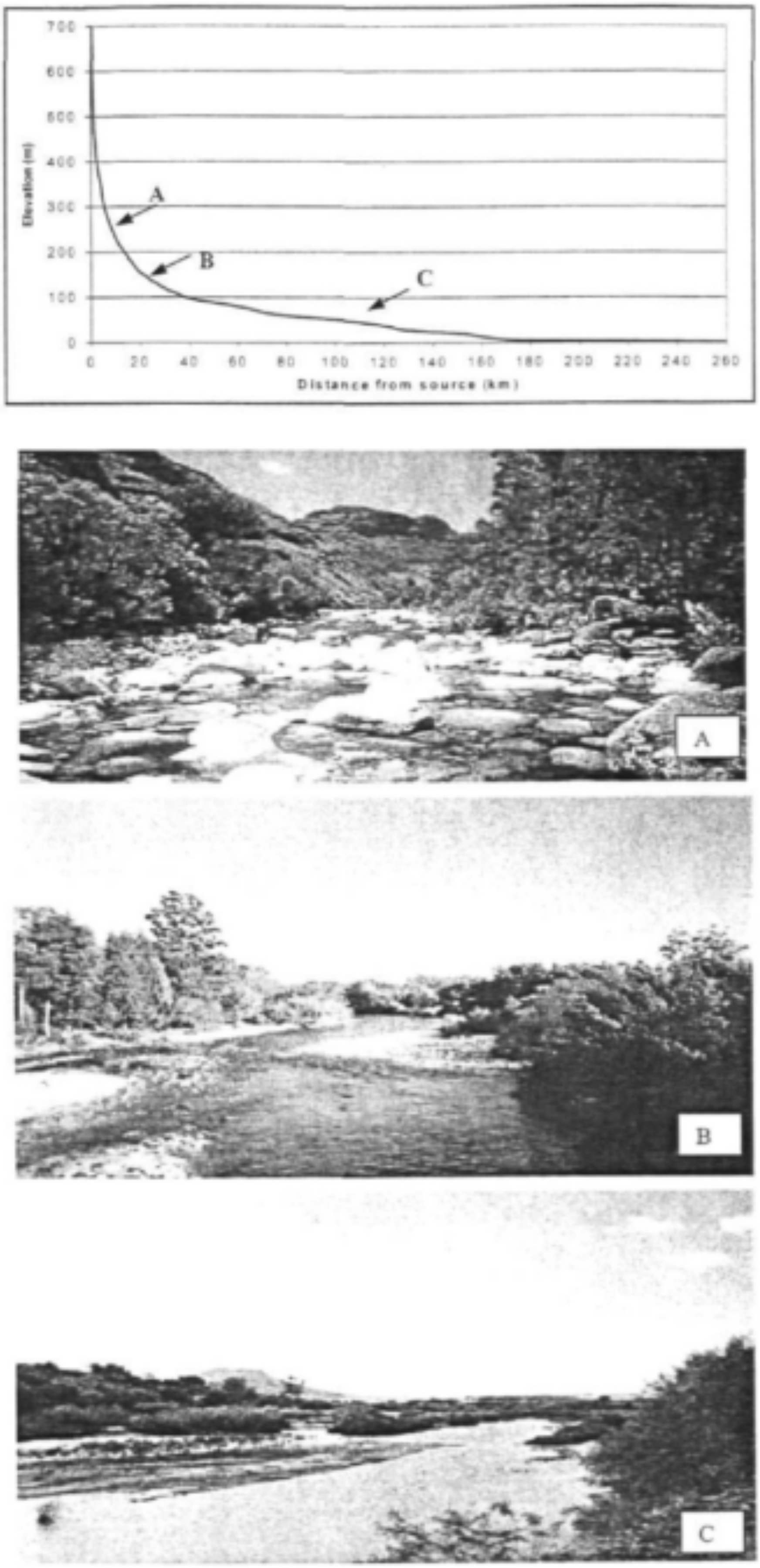


Figure 5.1 : Longitudinal profile and associated morphological characteristics in the Berg River

Study reach	Catchment name and area (km²)	Lat.	Long.	Longitudinal zone	Dominant substrate	Reach type	***Gradient (S_0) (%)
**Whitebridge	Jonkershoek (10)	33 59 37	18 58 40	Mountain	Boulder ; Bedrock	Step-Pool	5
**Jonkershoek	Jonkershoek (15)	33 59 20	18 58 01	Mountain trans.	Boulder	Pool-Rapid	2.7
*/**Vergenoeg	Jonkershoek (53)	33 56 10	18 53 35	Upper foothills	Cobble	Pool-Riffle	1.4
*/**Vlottenburg	Jonkershoek (192)	33 58 21	18 48 03	Lower foothills	Cobble	Pool-Riffle	0.7
Smalblaar	Breede (23)	33 43 50	19 06 50	Mountain trans.	Boulder ; Bedrock	Step-Pool	2.5
*/**Elands	Breede (61)	33 44 03	19 07 04	Upper foothills	Boulder	Pool-Rapid	1.3
*/**Molenaars I	Breede (92)	33 43 10	19 08 10	Upper foothills	Cobble	Pool-Riffle	0.8
*Molenaars II	Breede (111)	33 43 02	19 10 20	Upper foothills	Boulder	Pool-Rapid	1.2
**Berg I	Berg (20)	33 59 10	19 03 40	Mountain trans.	Boulder	Pool-Rapid	3.3
*/**Berg II	Berg (38)	33 57 30	19 04 10	Upper foothills	Boulder	Pool-Rapid	1.4
Berg III	Berg (172)	33 52 20	19 02 01	Upper foothills	Cobble	Pool-Riffle	0.8
*Berg IV	Berg (526)	33 45 04	18 56 21	Lower foothills	Cobble	Pool-Riffle	0.3
**Du Toits	Riviersonderend (21)	33 56 13	19 10 10	Mountain trans.	Boulder	Pool-Rapid	2.2

* Reaches in which the regime model was verified (refer to paragraph 5.3.3)

** Reaches in which hydraulic data were collected (refer to Chapters 8 and 9)

*** Determined from 1:10 000 orthophotos

Table 5.1 : List of study reaches

No chemical or biological data were collected. Only data on the physical (morphological) attributes of reaches were collected. This included :

i. Bed form geometry

Data on the spacing of morphological units (L), the local gradients of riffles and rapids (α_r) and the depth of pools (Δz) within each study reach were collected (refer to Figure 5.2). A dumpy level and staff were used and in some reaches the entire longitudinal profile was surveyed (attached as Appendix C).

ii. Channel width and depth

The channel width and depth (measured from the lowest point in the channel) at bankfull level at three transects in each study reach were surveyed. The transects represented, respectively, a pool, a riffle or rapid, and the length of channel in between. Average values of bankfull width (W_{ch}) and depth (D_{ch}) were then calculated for each reach.

iii. Substrate size distribution

The determination of substrate size distribution was based on the Wolman sampling method (Wolman, 1954), which included the following steps:

- In the reach under consideration, a grid system with 100 nodes was established over a length of 7 to 10 channel widths.
- The median diameters of the 100 substrate particles located underneath the nodal points on the grid, were measured.
- Based on the measured diameters, a cumulative frequency curve for each sample was plotted from which values of the median diameter (d_{50}) and other percentile values could be determined.

Cumulative frequency curves of the substrate size distributions within the various study reaches are included as Appendix D.

Table 5.2 summarizes all the data collected (Note that average values of L, α_r and Δz were calculated for each study reach).

Site	d_{50} (mm)	σ	W_{cb} (m)	D_{cb} (m)	L (m)	Δz (m)	α_r (%)
Whitebridge	200	0.431	10	1.1	14	0.40	10
Jonkershoek	215	0.398	8	1.5	25	0.50	6
Vergenoeg	170	0.389	15	1.3	50	0.60	3.1
Vlottenburg	140	0.181	22	1.9	95	0.80	2.4
Smalblaar	240	0.361	14	1.0	30	0.40	5.7
Elands	250	0.301	22	1.2	75	0.55	4.1
Molen. I	130	0.332	30	1.5	120	0.40	2.8
Molen. II	220	0.338	29	1.5	70	0.65	4.1
Berg I	275	0.331	15	1.3	55	0.45	7
Berg II	160	0.415	17	1.4	50	0.55	3.8
Berg III	170	0.220	30	1.4	110	0.55	2.5
Berg IV	90	0.239	38	1.8	145	0.65	1.6
Du Toits	150	0.417	14	0.9	30	0.40	4

Note: σ = standard deviation of bed particle size distribution = 0.5 log (d_{84}/d_{16})

Table 5.2 : Morphological data

5.2.3 Bed form geometry

Step-pool, pool-rapid and pool-riffle reaches may be defined by the parameters L, Δz and α_r as shown in Figure 5.2. In order to investigate the changes in bed form geometry along the length of the channel, the average values of L, Δz and α_r within each study reach were plotted against the average reach gradient as shown in Figure 5.3.

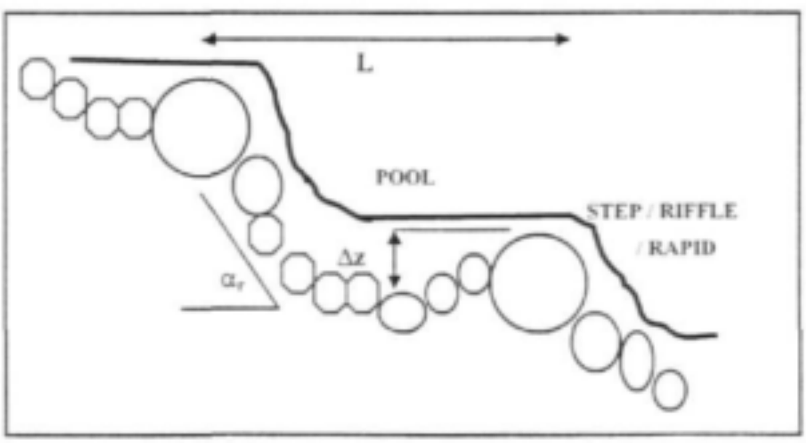


Figure 5.2 : Definition of reach parameters

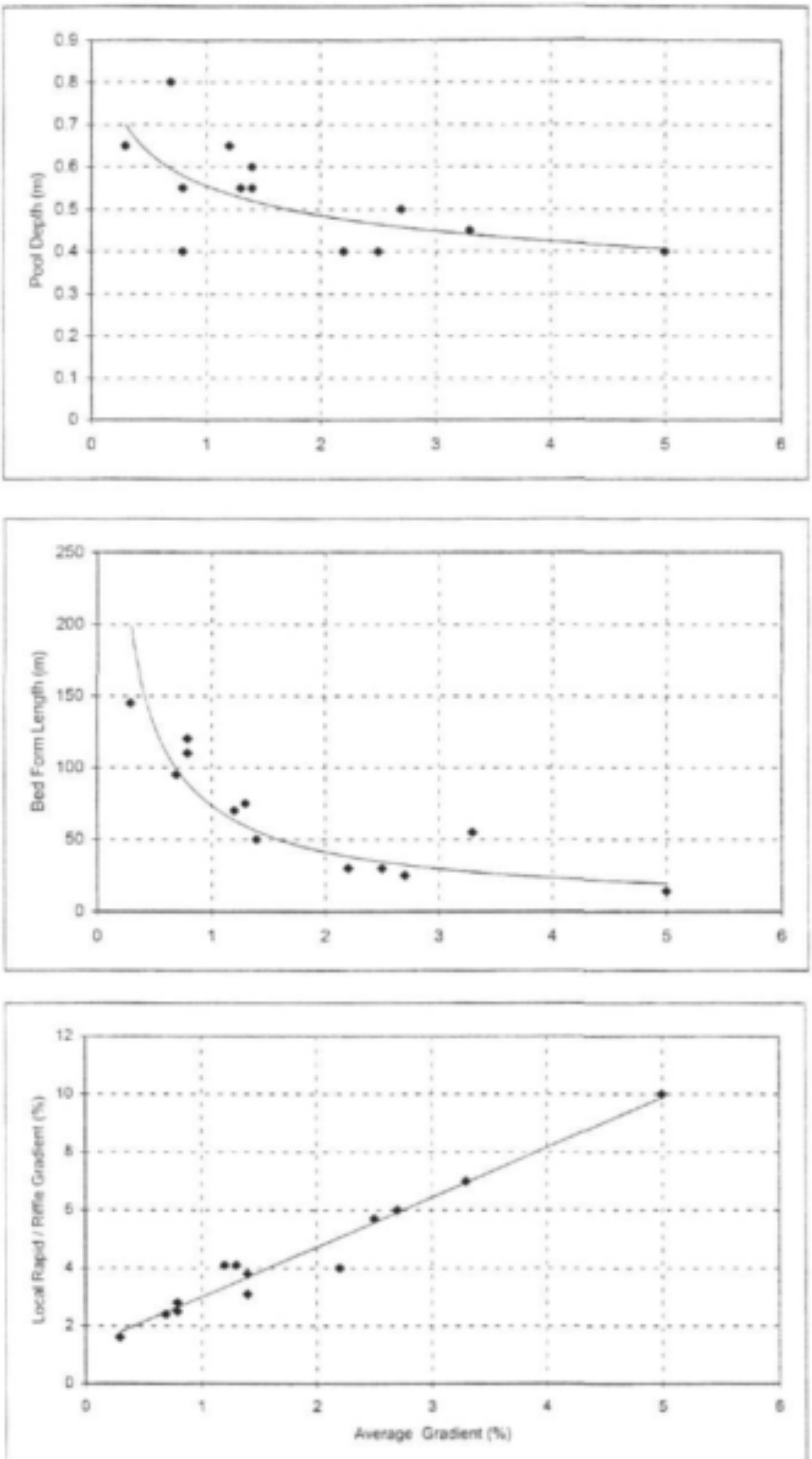


Figure 5.3 : Changes in macro bed form geometry with average channel gradient (reach-averaged values shown)

Figure 5.3 indicates that there is a definite correlation between the geometry of macro bed forms and their location within the longitudinal profile. It is found that:

- The local gradients of step, rapid and riffle morphological units increase in direct relation to the average channel gradient.
- The depth of pools tends to be slightly larger at the lower gradient reaches.
- The spacing of macro bed forms decreases with increasing channel gradient.

5.2.4 Channel geometry

A common feature of alluvial rivers with erodible boundaries is their consistency of form in relation to discharge. Channel width and depth, where both are measured at the bankfull level, are useful indices for describing channel form. Since, in the Western Cape, flood discharge typically increases with distance downstream because of the increasing area of drainage, the catchment area is often used to represent discharge. Downstream changes in bankfull width and depth as well as the ratio of bankfull width to depth in relation to catchment area for the various study reaches, are shown in Figure 5.4.

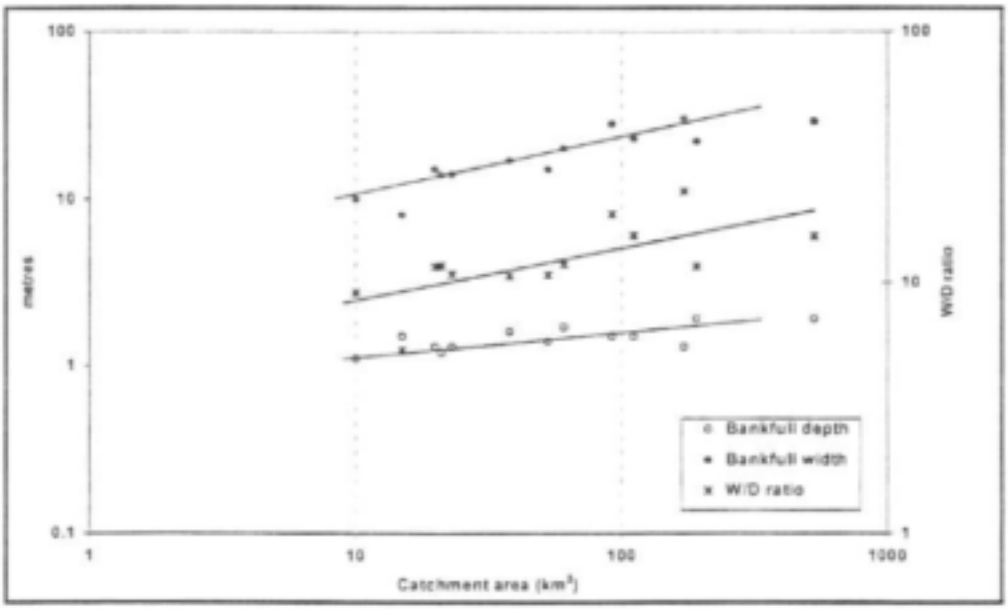


Figure 5.4 : Changes in channel geometry with catchment area

It shows that the magnitude of all three parameters increase in the downstream direction in direct relation to the catchment area. Furthermore it indicates that even though the various study reaches are situated in four different catchments, very similar relationships exist between catchment area and channel geometry and that a case can be made for regional consistency.

5.2.5 Substrate characteristics

The common feature of all rivers under consideration in this research project is the characteristic concave shape of the longitudinal profile in the downstream direction, with the slope decreasing from the upper "eroding" reaches to the lower "depositional" ones. This is typical of many alluvial streams and is associated with both an increase in discharge and a decrease in sediment particle diameter in the downstream direction. Figure 5.5, which indicates the relationship between particle size and average channel gradient within the study reaches, clearly indicates an increase in particle diameter size with channel gradient.

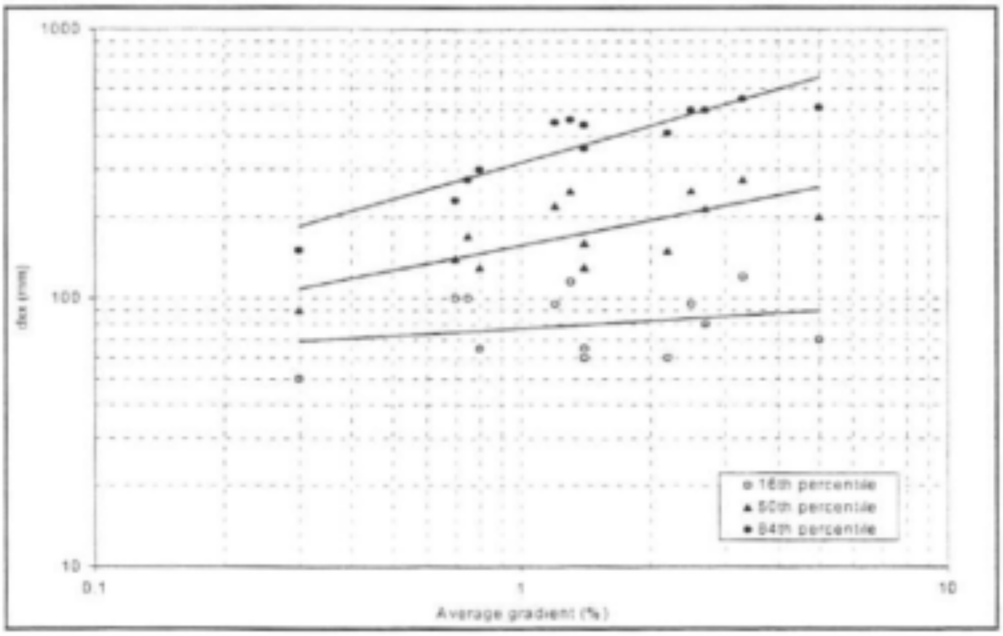


Figure 5.5 : The variation of substrate size with average channel gradient

Another common feature of cobble and boulder bed rivers, is the wide range of particle sizes within any particular reach. This variability in bed particle size may be represented by the standard deviation. Bathurst (1978) found that the size distributions of larger sized bed particles are approximately log-normal, in which case the standard deviation may be expressed as 0.5 log (d_{84}/d_{16}). Assuming that this is also applicable to the cobble and boulder bed rivers of the Western Cape, the standard deviation was expressed as 0.5 log (d_{84}/d_{16}).

Figure 5.6, which shows the relationship between the standard deviation in bed particle size and the average channel gradient within the study reaches, therefore suggests that the surface armouring particles become more uniform as one progresses down the river.

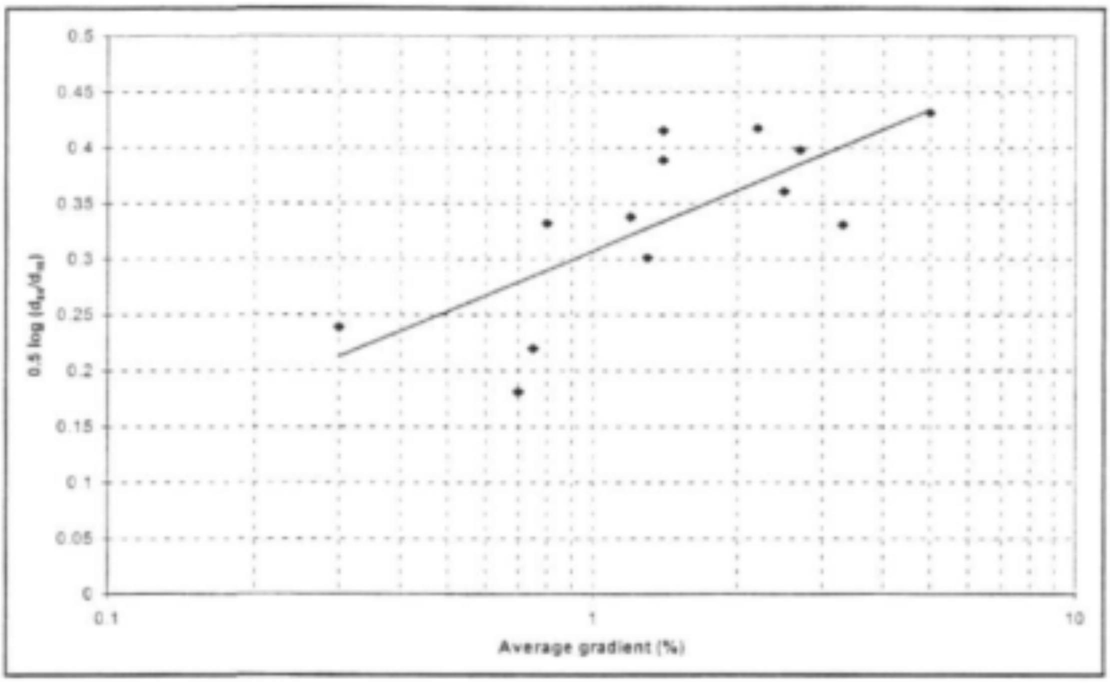


Figure 5.6 : The standard deviation in bed particle size vs. average channel gradient

5.3 The development of a regime model for cobble and boulder bed rivers

5.3.1 Background

Regime theory attempts to establish the relationships that exist within a river channel between a characteristic discharge, sediment characteristics, channel form and channel gradient. 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 subsequently been developed. These approaches 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. Although empirical regime methods are not based on theoretical considerations, the nature of their derivation and their history have resulted in general acceptance of their approximate representation of dominant channel deformation mechanisms (Le Grange, 1994). However, the inadequacy of the empirical methods in explaining the cause of the dynamic adjustment of rivers has prompted the development of the so-called 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". Various physical quantities have been considered which include the minimization of stream power hypothesis (Chang and Hill, 1977; Song and Yang, 1982), the maximum sediment transport rate hypothesis (White *et al.*, 1982), the maximum flow resistance hypothesis (Davies and Sutherland, 1983; Abrahams *et al.*, 1995) and the hypothesis of minimum unit stream power (Yang, 1984).

Since not all discharges have the same capacity to perform work, a critical issue related to regime theory is the identification of an appropriate discharge which "dominates" channel formation and which can be defined either in terms of its hydrological significance (linked to a certain return period, the long term average flow, the mean annual flood or rare and large floods), its hydraulic significance (bankfull flow or a flow which exceeds the critical shear velocity of the bed sediments) or both. Although some researchers support the concept that a range of discharges govern the shape and size of alluvial channels (Harvey, 1969; Knighton, 1984), it is often assumed when describing the regime behaviour of alluvial rivers that the bankfull discharge, the discharge that fills the river channel to its banks and above which spilling into the floodplain occurs, dominates the formation of the channel. This assumption is based on the results of numerous studies on the regime behaviour of alluvial rivers: Dury (1954) and Leopold and Wolman (1957) for example, demonstrated empirically that consistent relationships exist between bankfull discharge and the channel pattern, particularly the spacing of pools and riffles and the wavelength of meander bends. Similarly, Ackers and Charlton (1970), in an attempt to determine the discharge responsible for the meander geometry of sand bed streams, conducted experimental research and confirmed bankfull flow as the "condition which generates the characteristic meander length". Andrews (1980) found that the bankfull discharge is nearly equal to the effective discharge, defined as the increment of discharge that transports the largest fraction of the annual sediment load over a period of years, which can be assumed to play a dominant role in channel formation. Petts and Foster (1985) state that flow resistance reaches a minimum at bankfull stage and thus the channel operates most efficiently for the transport of water at this level. The significance of the bankfull discharge is further emphasized when its consistency in terms of frequency of occurrence is considered. Dury (1959, 1961) found that on certain English and American rivers bankfull discharge has a recurrence interval of between one and two years. In 1964, Leopold *et al.* found that recurrence intervals for natural bankfull discharge on nineteen American rivers range from 1 to 4 years and suggested a normal of 1 to 2 years. In recently incised channels in Australia, Woodyer (1968) used bench levels corresponding to the present floodplain level to derive average recurrence intervals between 1.2 and 2.7 years, while Andrews (1980) found that the recurrence interval of the effective (bankfull) discharge ranged from 1.2 to 3.3 years.

5.3.2 A review of existing regime models for rivers with large sized bed particles

Extensive research has been conducted to describe the regime behaviour of sand bed rivers and numerous sand bed regime models have been developed, including models that describe the development of small scale bed forms under lower and upper regime conditions. However, it is only until relatively recently that attention has been directed towards the regime characteristics of rivers with larger sized bed particles, i.e. gravel, cobble and boulder bed rivers, which are characterized by macro scale bed forms and unique flow conditions.

Generally, models which describe the regime behaviour of these rivers can be categorized into those that predict channel geometry, i.e. channel width, depth and gradient and those that address the formation of macro scale bed forms.

i. Channel geometry

Since 1960, various equations have been derived for predicting the regime dimensions of stable gravel and cobble bed rivers. Most of these are of the same form and relate channel width (W_{ch}), depth (D_{ch}) and gradient (S_0) to one or more independent variables, viz. a characteristic discharge (Q), sediment discharge (Q_s) and a characteristic bed particle diameter (d_{xx}). (Some equations also accommodate the effect of vegetation type found on the river banks.)

Table 5.3 lists some of the existing empirical regime equations for gravel and cobble bed rivers. The derivation of these equations were either restricted to straight channels with plane beds or define reach averaged values of channel width, depth and gradient, with no account being taken of the pool-riffle variability characteristic of these rivers.

Reference	**Channel Width (m)**	**Channel Depth (m)**	**Channel Gradient**	**d_{50} (mm)**
Kellerhals (1967)	$3.26Q_{bf}^{0.50}$	$0.182d_{90}^{-0.12}Q_{bf}^{0.40}$	$0.086d_{90}^{0.92}Q_{bf}^{-0.40}$	-
Hey (1982)	$2.2Q_s^{-0.05}Q_{bf}^{0.54}$	$0.16d_{50}^{-0.15}Q_{bf}^{0.41}$	$0.68Q_s^{0.13}d_{50}^{0.97}Q_{bf}^{-0.35}$	21 – 90
Bray (1982)	$2.08d_{50}^{-0.07}Q_2^{0.53}$	$0.26d_{50}^{-0.025}Q_2^{0.33}$	$0.097d_{50}^{0.586}Q_2^{-0.334}$	19 - 145
Hey & Thorne(1984)				
(Veg. I)	$3.98Q_{bf}^{0.54}\ Q_s^{-0.01}$	$0.16Q_s^{-0.02}d_{50}^{-0.15}Q_{bf}^{0.39}$	$0.087Q_s^{0.1}d_{50}^{-0.09}Q_{bf}^{-0.43}$	10 – 180
(Veg. II)	$3.08Q_{bf}^{0.54}\ Q_s^{-0.01}$	$0.19Q_s^{-0.02}d_{50}^{-0.15}Q_{bf}^{0.39}$	$0.087Q_s^{0.1}d_{50}^{-0.09}Q_{bf}^{-0.43}$	10 – 180
(Veg. III)	$2.52Q_{bf}^{0.54}\ Q_s^{-0.01}$	$0.19Q_s^{-0.02}d_{50}^{-0.15}Q_{bf}^{0.39}$	$0.087Q_s^{0.1}d_{50}^{-0.09}Q_{bf}^{-0.43}$	10 – 180
(Veg. IV)	$2.17Q_{bf}^{0.54}\ Q_s^{-0.01}$	$0.20Q_s^{-0.02}d_{50}^{-0.15}Q_{bf}^{0.39}$	$0.087Q_s^{0.1}d_{50}^{-0.09}Q_{bf}^{-0.43}$	10 – 180

Q_{bf}: Bankfull discharge; Q_2: Two year flood discharge; Veg. I: Grassy banks with no trees or shrubs; Veg. II: 1-5% tree/shrub cover; Veg. III: 5-50% tree/shrub cover; Veg. IV: >50% shrub cover or incised into flood plain

Table 5.3 : Empirical regime equations for gravel and cobble bed rivers

To address the local variability in channel geometry due to the presence of pools and riffles, Hey and Thorne (1986) evaluated data from 62 stable gravel and cobble bed rivers (d_{50} between 14 mm and 176 mm). They found that on average at bankfull stage, the channel at riffles is 3.4 % wider and 5 % shallower than the average bankfull width and depth respectively, while the channel at pools is 3 % narrower and 5 % deeper than the average bankfull width and depth respectively

The earliest rational analyses for describing the regime geometry of river channels with large sized bed particles (> 2 mm) were based on the threshold theory and related the flow conditions and channel form to the incipient motion of the bed particles and bank stability (Glover and Florey, 1951; Lane *et al.*, 1959; Li *et al.*, 1976). In 1980, Chang developed a rational regime model for gravel and cobble bed streams based on the concept of minimum stream power. He reasoned that for an alluvial channel, the necessary condition of equilibrium occurs when the stream power per unit channel length is a minimum. He subsequently derived the following equations describing the regime channel width, depth and gradient of gravel and cobble bed rivers (16mm $<d_{50}<$ 265mm): (note that the relevant dimensions in equations 5.1 to 5.3 are in feet and cubic feet per second):

$$W_{ch} = \left[1.905 + 0.249\left(\ln \frac{0.001065\ d_{50}^{\ 1.15}}{S_0 Q_{bf}^{\ 0.42}}\right)^2\right] Q_{bf}^{\ 0.47} \qquad (5.1)$$

$$D_{ch} = \left[0.2077 + 0.0418\ \ln\left(\frac{0.000442\ d_{50}^{\ 1.15}}{S_0 Q_{bf}^{\ 0.42}}\right)\right] Q_{bf}^{\ 0.42} \qquad (5.2)$$

$$S_0 = 0.000442\ d_{50}^{\ 1.15} Q_{bf}^{\ -0.42} \qquad (5.3)$$

Another example of a rational regime model for describing the geometry of gravel and cobble bed rivers, is that of Yalin (1992), who used a dimensional formulation of the regime channel to show that the Froude number is the only parameter, apart from channel width, depth and gradient, which varies during channel deformation. He concluded that the Froude number tends towards an extremal (minimum) value during regime channel formation and in conjunction with the Chézy equation and setting the critical shear velocity equal to 0.90 $d_{50}^{0.5}$, defined the following dimensional, non-homogeneous relationships which were calibrated with experimental data from rivers (14mm $<d_{50}<$ 190mm):

$$W_{ch} = 1.50\ d_{50}^{\ -0.25} Q_{bf}^{\ 0.50} \qquad (5.4)$$

$$D_{ch} = 0.15\ d_{50}^{\ -0.07} Q_{bf}^{\ 0.43} \qquad (5.5)$$

$$S_0 = 0.55\ d_{50}^{\ 1.07} Q_{bf}^{\ -0.43} \qquad (5.6)$$

ii. Macro scale bed deformation

Macro scale bed deformation in gravel, cobble and boulder bed rivers typically refers to the formation of riffles (or rapids) and pools. 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 reaches, which displayed a high degree of sinuosity and were not representative of pool-riffle or pool-rapid sequences characteristic of the middle and upper reaches. Three theories 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, dispersion and sorting theory and velocity reversal theory.

The antidune theory assumes that the formation of macro bed forms in gravel, cobble and boulder bed rivers corresponds to the formation of antidunes in sand bed rivers, where the wave form of the bed is in phase with the form of a standing wave on the water surface. Shaw and Kellerhals (1977) used equations developed by Kennedy (1961), Reynolds (1965) and Parker (1975), which link the dimensions of antidunes in sand with the corresponding flow parameters, and found a similarity between bed forms observed in a gravel bed river and gravel antidunes developed in the laboratory. However, in both cases (the river and laboratory) the bed material was fairly uniform and not representative of typical heterogeneous bed material found in cobble and boulder bed rivers. Furthermore, the bedforms, which they described as "transverse ridges more or less evenly spaced in the direction of flow with crests 2 m long and a crest spacing of 2 to 3 m", do not resemble typical pool-riffle or pool-rapid sequences. Whittaker and Jaeggi (1982) and Chin (1999) applied the antidune theory to step-pool systems. They found that although the deformation process leading an initial plane bed to step-pool formation is similar to that which produces antidunes, effects due to the heterogeneity of the bed sediments disturb the regularity of the process. They concluded that true antidune wave trains may apply only in some cases under natural conditions, such as along the more gentle reaches of the channel where bedforms are more adjustable and easily submerged, but are difficult to achieve in steeper channels dominated by larger roughness elements.

The second theory, the so-called dispersion and sorting theory of Yang (1971), applies the entropy concept introduced by Leopold and Langbein (1962) to a stream system which leads to the law of least time rate of energy expenditure. This law states that "during the evolution towards its equilibrium condition, a natural stream chooses its course of flow so that the time rate of potential energy expenditure per unit mass of water along its course, is a minimum". In combination with the continuity principle and a resistance equation, Yang (1971) developed a conceptual model which proved that when the discharge, lateral geometry and other constraints are the same for all possible courses between two points in space, the course of uniform depth and slope is the course of maximum time rate of potential energy expenditure per unit mass of water. Subsequently, this course will be avoided by natural streams and as a result, pools and riffles will be formed. The actual formation of riffles and pools, Yang ascribed to pressure differences between the riffle and pool areas, which will increase bed elevation at the riffles as coarse materials migrate to the surface due to a grain dispersion process as reported by Bagnold (1954). With reference to this proposed formation process, Whittaker and Jaeggi (1982) state that "for these effects to occur, the whole bed must be in a state of general shearing motion to a considerable depth, which in a gravel river, would only occur under debris flow conditions". Furthermore, Yalin's proposed mechanism for the formation of pool-riffle sequences has never been verified with field or laboratory experiments and no evidence for the proposed pressure differences between pools and riffles exist.

The third theory, which is known as the velocity reversal theory, was developed by Keller (1971). He measured velocities in pools and riffles and found that, with increasing discharge, there is a greater increase in velocity in the pools than along the riffles. From extrapolation of his data, he concluded that there would be a velocity reversal at high flows, which would move coarse grains from a riffle, through the subsequent pool, to be deposited in the next riffle, thus maintaining the feature. Although the theory appears in standard texts (Richards, 1982; Gordon *et al*., 1992) and underpins various conceptual models related to the pool-riffle structure (e.g. Keller and Melhorn, 1974; Andrews, 1982; Lisle, 1979; Sidle, 1988), convincing evidence for the ubiquitous occurrence of such a reversal in a range of channel geometries is currently unavailable (Carling, 1991). Carling (1991), who reviewed the theory as well as attempts to validate it, concluded that, based on continuity considerations, riffles need to be considerably wider than pools for a reversal in the velocity to occur under conditions of high stage and stable morphology. Referring to studies which demonstrate a velocity and shear stress reversal in the East Fork River in England (Andrews, 1979; Lisle, 1979), Carling states that the observed velocity reversal can be ascribed to the unique fact that the riffle where the reversal occurred was 74 % wider than the pool at bankfull stage! Furthermore, based on observations of the hydraulic geometry of stable pool-riffle sequences in the river Severn in England, Carling found that neither the sectionally-averaged velocity, nor the near-bed shear velocity was sensibly greater in the pools than over the riffles during bankfull or near bankfull flow. Instead, he noted a tendency towards equalization of the values of average hydraulic variables as discharge increases. Another objection to the velocity reversal theory is made by Bhowmik and Demissie (1982), who argue that, because of the supposedly higher shear stresses in pools during higher flows, the lag sediments in the bottom of pools should be coarser than the riffle sediments – a statement which is in conflict with numerous observations that material in riffles is generally coarser than those in pools (Hircsh and Abrahams, 1981; Milne, 1982). Further criticism of the velocity reversal theory is made by Whittaker and Jaeggi (1982), who state that the proposed mechanism is essentially one of maintenance of pool-riffle bed forms and fail to explain the development thereof.

5.3.3 An analytical approach towards the development of a model for predicting the regime characteristics of cobble and boulder bed rivers

The above review of existing regime models for rivers with large sized bed particles revealed that none of these models provide a complete morphological description in terms of those attributes which are important for ecosystem functioning, viz. substrate characteristics, pool depths, the local gradients of riffles and rapids which affect turbulence and the spacing or frequency of bed forms. Whereas the equations which relate a characteristic discharge to channel geometry only provide information on channel width, depth and average gradient, the proposed theories on macro scale bed deformation are essentially conceptual models describing the process of bed deformation without providing quantifiable relationships between discharge, channel geometry and bed form geometry. In order to predict the environmental impacts associated with a modified flow regime, an understanding of the relationships between the channel forming discharge and the ecologically relevant morphological attributes is required. In this section these relationships are investigated and a model is proposed for predicting the regime characteristics of cobble and boulder bed rivers.

i. Hypothesis

Cobble and boulder bed reaches typically occur in the upper catchment areas and are characterized by steep gradients. During higher flows, this results in extremely high shear velocities along the river bed which may lead to large scale erosion. Consistent with theories by Keller and Melhorn (1978), Leopold *et al.* (1964) and Yang (1971), it is therefore hypothesized that the formation of pools and riffles is essentially a mechanism of self-adjustment by the stream system towards obtaining dynamic equilibrium. This is achieved by reducing the erosive capacity of the river through the effective dissipation of excess energy. By transforming the bed profile into a series of macro scale bed forms, each of which acts as a natural control structure, the water is forced through critical depth with a subsequent hydraulic jump downstream. Furthermore, during this bed deformation process, the river is removing smaller bed particles from the river bed and in so doing, increases the effective absolute roughness which leads to a reduction in the amount of unit turbulent stream power applied along the river bed as well as in the sediment transport capacity of the river. Channel and bed deformation therefore continues until, on average along the river bed, the rate of deposition of particles equals the rate of resuspension. At this point, in similar fashion to a sand bed river under conditions of dynamic equilibrium (Rooseboom and Le Grange 2000), it follows that individual bed particles are continually crossing the movement threshold, i.e. critical conditions in terms of sediment movement prevails.

With reference to Figure 5.7, which displays a schematic representation of the hydraulic conditions assumed to prevail during bed deformation, the hypothesis therefore states that at each start of a riffle or rapid a control section exists where the energy level is minimized and the flow depth is critical. After passing the control section, the water accelerates down the slope to form a so-called riffle or rapid. The momentum of the fast flowing water is checked by the slower moving water in the pool, with the water level in the pool being determined by the energy level at the start of the next (downstream) riffle or rapid and so on. The flow depth in the pool is therefore linked directly to the flow velocity of the water that enters the pool, which in turn, is determined by the local gradient and roughness of the riffle at a specific discharge. When equilibrium conditions prevail, the flow depth of the water in the pool is just sufficient to dissipate the excess energy without nett removal of sediment from the bed, while the flow depth along the riffle or rapid is just sufficient to equal the momentum of the water in the pool, without net removal of sediment from the riffle area. At a characteristic discharge and bed particle size distribution therefore, the river adjusts its width, average gradient, local gradient of the riffle or rapid, absolute roughness and scour depth in the pool until equilibrium exists in terms of the power applied along the bed and the power required to suspend bed particles as well as in terms of momentum exchange between the accelerating water along the riffle and the slower moving water in the pool.

The hypothesis therefore implies that consistent relationships should exist between channel geometry, the configuration of the macro bed forms, the critical shear velocity of bed particles (related to bed particle size) and a characteristic discharge.

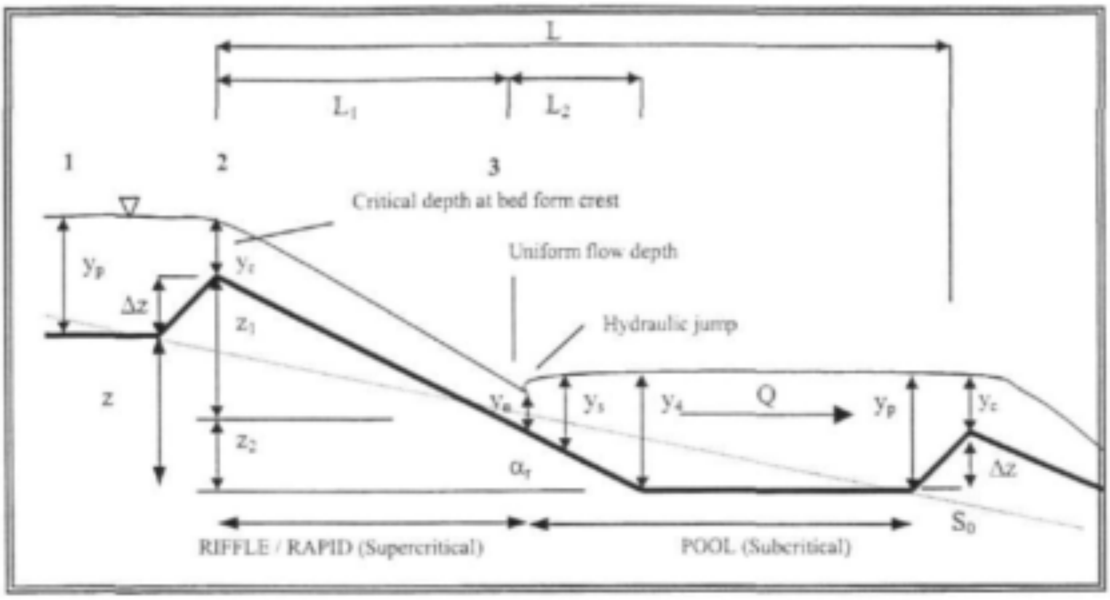


Figure 5.7 : Schematic representation of the hydraulic conditions prevailing during macro scale bed deformation (not to scale)

ii. The relationship between bed configuration and discharge

As a first step towards the development of the model, the relationship between the channel forming discharge and the bed geometry in a deformed cobble and boulder bed river (as depicted in Figure 5.7) was defined, through application of the energy and momentum principles and based on certain assumptions. Equations 5.7 to 5.16 were subsequently derived:

Applying the energy principle between sections 2 and 3 and assuming uniform flow depth (y_n) at the start of the hydraulic jump, it follows that

$$z_1 + y_c + V_c^2/2g = y_n + V_n^2/2g + h_f \qquad (5.7)$$

with z_1 : bed elevation above datum (m)

y_c : critical flow depth (m)

y_n : uniform flow depth m)

V_c : average flow velocity at bed form crest $= Q / (W_{ch}y_c)$ (m/s)

V_n : average flow velocity at section 3 $= Q / (W_{ch}y_n)$ (m/s)

h_f : friction losses along the riffle/rapid (m)

However,

$$h_f = S_f\, L_1$$
$$= S_f\, z_1 / \tan \alpha_r$$
$$\approx \quad \frac{z_1}{2\alpha_r}\left[\frac{V_c^{\,2} f}{8 g y_c} + \frac{V_n^{\,2} f}{8 g y_n}\right] \tag{5.8}$$

with S_f : energy gradient along riffle / rapid

g : gravitational acceleration (m/s^2)

f : Darcy-Weisbach resistance coefficient

Therefore, from equations 5.7 and 5.8:

$$z_1 = \frac{\left(y_n + V_n^{\,2}/2g - y_c - V_c^{\,2}/2g\right)}{1 - \frac{0.5}{\alpha_r}\left(V_c^{\,2} f / 8 g y_c + V_n^{\,2} f / 8 g y_n\right)} \tag{5.9}$$

Furthermore, from the momentum principle, it can be shown that

$$y_s = \frac{y_n}{2}\left[\sqrt{1 + \frac{8 V_n^{\,2}}{g y_n}} - 1\right] \tag{5.10}$$

Bradley and Peterka (1957) showed that in the case of a hydraulic jump on a sloped surface, the equivalent sequent flow depth on a horizontal surface is defined by (refer to Figure 5.7)

$$y_4 = 1.3\, y_s \tag{5.11}$$

and, based on experimental data, they found that

$$L_2 = 0.82\, y_s\, (\tan \alpha_r)^{-0.78} \tag{5.12}$$

Next, assuming that energy losses within the pool are negligible, $y_p \approx y_4$. If it is assumed that at the channel forming discharge, the height (Δz) of the control section is just sufficient to force the water through critical depth at the bed form crest, it follows that

$$\Delta z = (y_p + V_p^{\,2}/2g - y_c - V_c^{\,2}/2g) \tag{5.13}$$

Furthermore, from Figure 5.7

$$z = z_1 + z_2 - \Delta z \quad (5.14)$$

and

$$z_2 = L_2 \tan \alpha_r \quad (5.15)$$

and assuming that a consistent relationship will exist between the height of a bed form (z), the length of the bed form (L) and the average gradient of the reach (S_0), i.e. that the spacing of bed forms fits in with the channel topography, the length of a bed form (L) may be calculated from the channel topography as follows:

$$L = z / S_0 \quad (5.16)$$

Equations 5.7 to 5.16 therefore define relationships between a channel forming discharge, channel geometry and bed form geometry within a typical pool-riffle unit, which enable the hypothesis on the formation of macro scale bed forms in cobble and boulder bed rivers to be verified

iii. Verification

The morphological data which were collected in the study reaches as listed in Table 5.1, were used to verify the above hypothesis on channel deformation. (Some of the study reaches in the mountain and mountain transitional zones (Whitebridge, Jonkershoek, Smalblaar and Berg I), which are characterized by large clasts of rocky material which have found their way into the river by falling down from steep banks and cliffs alongside the river, were not included in this analysis. The Du Toits and Berg III reaches were also excluded due to the fact that they were situated close to a weir and bridge crossing respectively.) The following procedure was followed:

The channel forming discharge

Equations 5.7 to 5.16 were applied to the study reaches and from the observed channel and bed form geometry within each reach, a characteristic discharge (Q_c) which, according to the hypothesis, represents the discharge prevailing during macro scale bed deformation, was calculated. This involved a repetitive process whereby the measured values of channel width, the local gradient of the riffle or rapid and the average reach gradient were substituted into the equations and a discharge selected and refined until the calculated value of the bed form length equalled the measured value thereof. (In order to make provision for the effects of large scale roughness, the value of the Darcy Weisbach resistance coefficient in equations 5.8 and 5.9 were calculated from equation 6.7 (Griffiths, 1981), which, as shown in Chapter 6, has been found to provide a good estimate of flow resistance in the cobble and boulder bed rivers of the Western Cape.)

Hydrological significance

For those study reaches where observed peak flow records at nearby gauging weirs were available, the calculated values of Q_c were compared with the results of an annual flood frequency analysis (see Table 5.4 and Appendix E). The results confirm that within all these reaches, Q_c corresponds to floods with a recurrence interval of between 1 and 4 years. The significance of this is further emphasized when considering that floods with a recurrence interval of between 1 and 3 years have been shown to be equivalent to the bankfull or "dominant" discharge (refer to section 5.3.1).

Reach (gauging station)	Q_c (m^3/s)	Recurrence interval (Years)
Elands (H1H017/33)	203	3.84
Molenaars I (H1H018)	281	1.43
Molenaars II (H1H018)	222	1.20
Berg IV (G1H020)	243	1.53

Table 5.4: The recurrence interval of the characteristic discharge (Q_c)

Critical conditions for sediment movement

In section 5.3.3 (i) it was hypothesized that the regime or equilibrium condition in a deformed cobble and boulder bed river is characterized by critical conditions in terms of sediment movement, which implies that at the characteristic discharge (Q_c) calculated above, critical conditions for sediment movement prevails. With the aid of field data collected in the study reaches, this was subsequently verified.

Because of the variation in hydraulic conditions during macro scale bed deformation (as depicted in Figure 5.7) different areas along the river bed will be characterized by different shear velocities during the channel deformation process. Three distinct areas within the deformed bed profile were therefore identified where the relationship between actual shear velocity and critical shear velocity was investigated, viz. at the bed form crest, along the riffle or rapid and within the pool.

Within each of these areas, the shear velocity (V^*) was calculated from equation 5.17:

$$V^* = \sqrt{gyS_f} \tag{5.17}$$

with
- y : flow depth
- S_f : energy gradient $= (V^2 f)/(8gR)$
- V : average flow velocity $= Q_c / (W_{ch}y)$
- R : hydraulic radius (assumed equal to y)
- f : Darcy Weisbach coefficient (calculated form equation 6.7)

Assuming a rectangular channel, the critical flow depth at the bed form crest was calculated from equation 5.18:

$$y_c = \sqrt[3]{\frac{Q^2_c}{gW_{ch}^{\ 2}}} \tag{5.18}$$

Along the riffle (or rapid), the flow depth was assumed equal to the uniform flow depth (y_n), which was calculated by solving equation 5.19:

$$Q_c = y_n W_{ch} \sqrt{\frac{8gy_n S_f}{f}} \tag{5.19}$$

Within the pool, the flow depth (y_p) was calculated by solving equation 5.20

$$y_p + \frac{\left(Q_c / W_{ch} y_p\right)^2}{2g} = \Delta z + 1.5y_c \tag{5.20}$$

Critical shear velocities (V^*_{cr}) were calculated from equation 5.21 (Rooseboom, 1974), which represents the initiation of movement of a cohesionless sediment particle under uniform, turbulent boundary conditions.

$$V^*_{cr} = 0.12V_{ss} \tag{5.21}$$

with V_{ss} representing the settling velocity of a sediment particle under turbulent flow conditions, i.e.

$$V_{ss} = \sqrt{\frac{4(\rho_s - \rho)gd_s}{3\rho C_d}} \tag{5.22}$$

with ρ_s : substrate particle density (kg/m^3) - set equal to 2670 kg/m^3 as determined from actual river cobbles.

ρ : water density (kg/m^3)

d_s : characteristic particle diameter (m)

C_d : drag coefficient

If the value of C_d in equation 5.22 is assumed constant (=0.4), which is true for larger diameters, it follows from equations 5.21 and 5.22 that the critical shear velocity of a bed particle (V^*_{cr}) is directly related to the square root of its diameter $\sqrt{d}$.

In order to make provision for the effect of gravity along the riffle or rapid, which may be significant due to the steep gradient and which may contribute to particle mobility in this area, the critical shear velocity along the riffle/rapid was reduced with a coefficient calculated from equation 5.23 (Armitage, 2002):

$$C_m = \sqrt{\cos\alpha_r\left(1 - \frac{\tan\alpha_r}{\tan\phi}\right)} \tag{5.23}$$

with C_m : mobility coefficient

ϕ : angle of repose (≈ 40° for large bed particles (Van Rijn, 1993))

Figure 5.8, which displays the degree of correlation between the shear velocities and critical shear velocities related to different percentile values of the overall substrate size distribution within the reach, shows that at different locations within the various study reaches, the shear velocity at a discharge equal to Q_c consistently approximates the critical shear velocity for a certain particle size (±d_{95} in rapids or riffles, ±d_{84} at the crest and ±d_{35} in pools). This confirms that consistent relationships exist between bed form geometry and the bed particle size distribution at the characteristic discharge. It also confirms the hypothesis that critical conditions in terms of sediment movement may be assumed to prevail along the bed in a deformed cobble and boulder bed river. The different values of critical shear velocity at the different locations, which reflect the different particle sizes that are in equilibrium in terms of the effective shear velocity (related to the power applied along the river bed) and the critical shear velocity (related to the power required to suspend the bed particles), may be attributed to the differences in armouring effects as well as whether gravity works against or with movement.

Furthermore, the results of the above analysis, which showed that at a discharge of Q_c, the river is able to remove larger particles from the riffle areas (up to the 95^{th} percentile value) than from the pool areas (up to the 35^{th} percentile value), are consistent with a statement by Leopold *et al.* (1964) that higher shear velocities at the riffles cause finer material to be washed away and deposited in the pools downstream. Only the coarser particles which can withstand the higher bed shear stress therefore remain at the riffle. It is also in agreement with the findings of Andrews (1983), who found that particles as large as the d_{90} of the substrate size distribution were entrained by the bankfull discharge in nine Colorado rivers, as well as with numerous observations that rapids and riffles exhibit relatively coarser bed particles than pools (Leopold *et al.*, 1964; Bhowmik and Demissie, 1982; Keller, 1971; Church, 1972; Lisle, 1979; Richards, 1976; Hirsch and Abrahams, 1981; Milne, 1982). Finally, the above results are also supported by Hirsch and Abrahams (1981), who found that the bed sediments in riffle sections are not only coarser than in pools, but also better sorted – a finding which is expected when one considers that smaller sized particles are washed away from the riffles, leaving larger and more uniform particles behind.

Channel geometry

As discussed in section 5.3.1, bankfull discharge (Q_{bf}) is often considered to be responsible for determining the form of alluvial channels. Consequently it may be assumed that the characteristic discharge (Q_c) which was calculated above and which, in accordance with the adopted hypothesis is responsible for channel deformation, should approximate the bankfull discharge. As no measured data on observed bankfull discharges in the study reaches were available, an indirect approach was followed to investigate the relationship between Q_c and Q_{bf}.

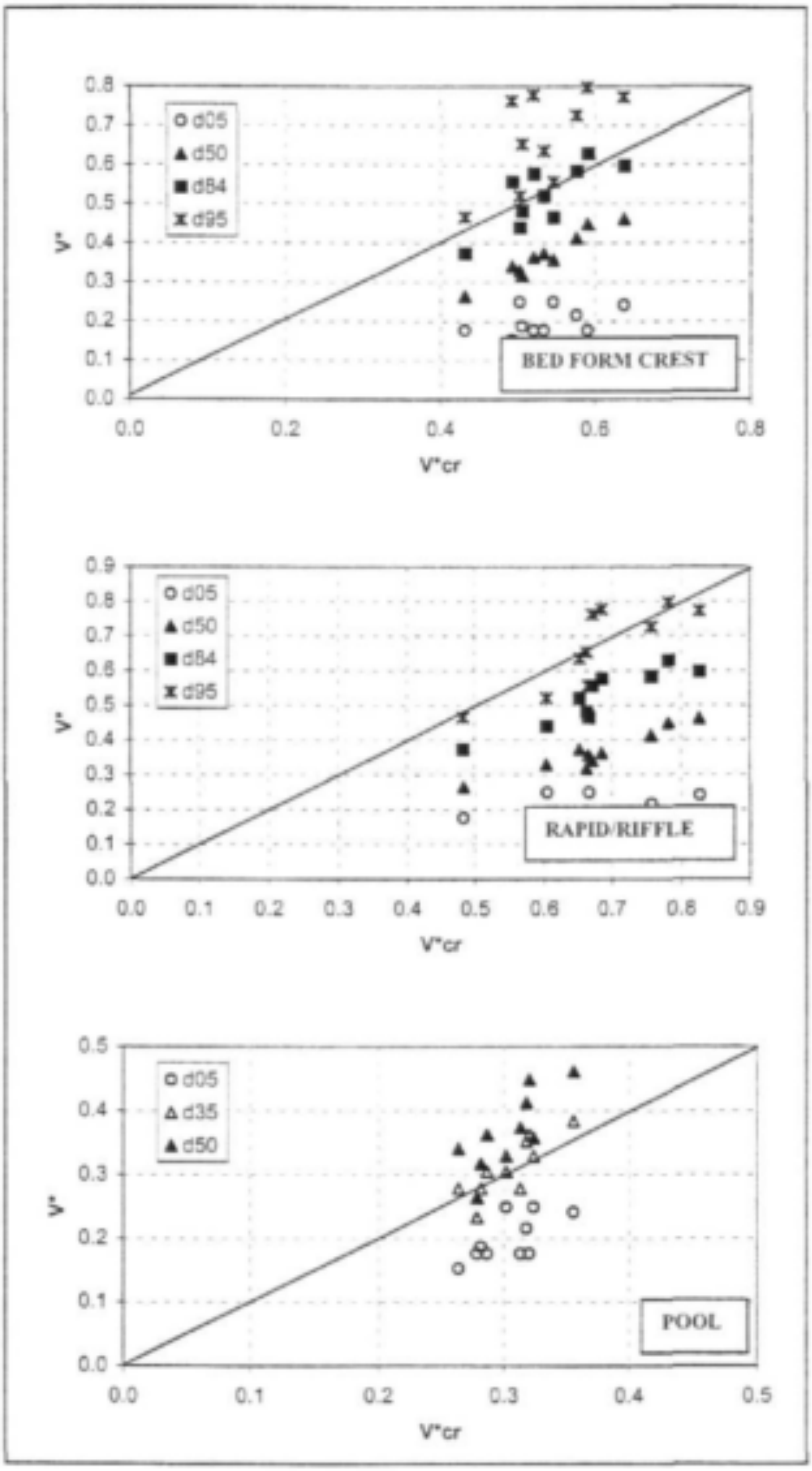


Figure 5.8 : The relationship between shear velocity (V*) and critical shear velocity (V^*_{cr}) at a discharge equal to Q_c

As explained previously, Q_c was calculated based on measured values of bankfull width, the average reach gradient, the local riffle gradient, the bed form length and the substrate size distribution within each study reach. Therefore, since the measured channel depth at bankfull level was not included in the calculations, a comparison of the observed channel depths at bankfull level and the calculated flow depths associated with Q_c provide an independent verification of the relationship between Q_c and Q_{bf} (Figure 5.9). It shows that, while the observed bankfull depths at the riffle sections are comparable to the calculated flow depths along the riffles at Q_c, the calculated pool depths at a discharge of Q_c are substantially larger than the observed values. A possible explanation might be that the large flow depths calculated in the pool areas only occur under dynamic equilibrium conditions. However, as the flow rate and sediment transport capacity of the river decreases, bed particles are being deposited in the pool areas, which leads to shallower pools being observed during low flow conditions.

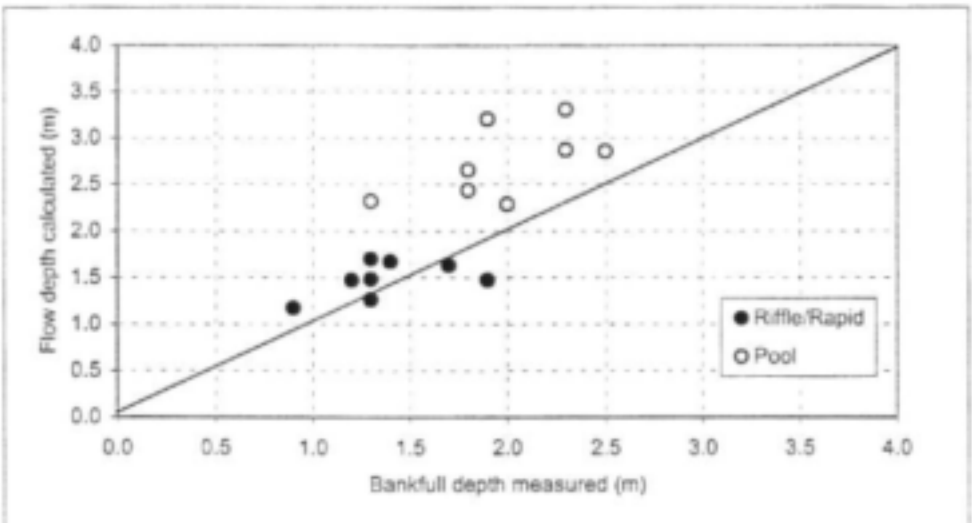


Figure 5.9 : The relationship between observed bankfull depth and flow depths associated with the characteristic discharge

Another methodology which was employed for investigating the relationship between Q_c and Q_{bf}, involved an estimation of channel geometry from existing regime equations at a discharge equal to Q_c, and a comparison of the calculated values of channel width, depth and gradient with observed values. The equations (equations 5.4 to 5.6) developed by Yalin (1992) were used which, according to him, can be regarded as "averages" of various regime equations. Figure 5.10 displays the degree of correspondence between the calculated and observed values of channel geometry and shows that good correlation exists between the observed and calculated values of channel width, depth and gradient, which indirectly therefore implies that there is good correlation between Q_c and Q_{bf}.

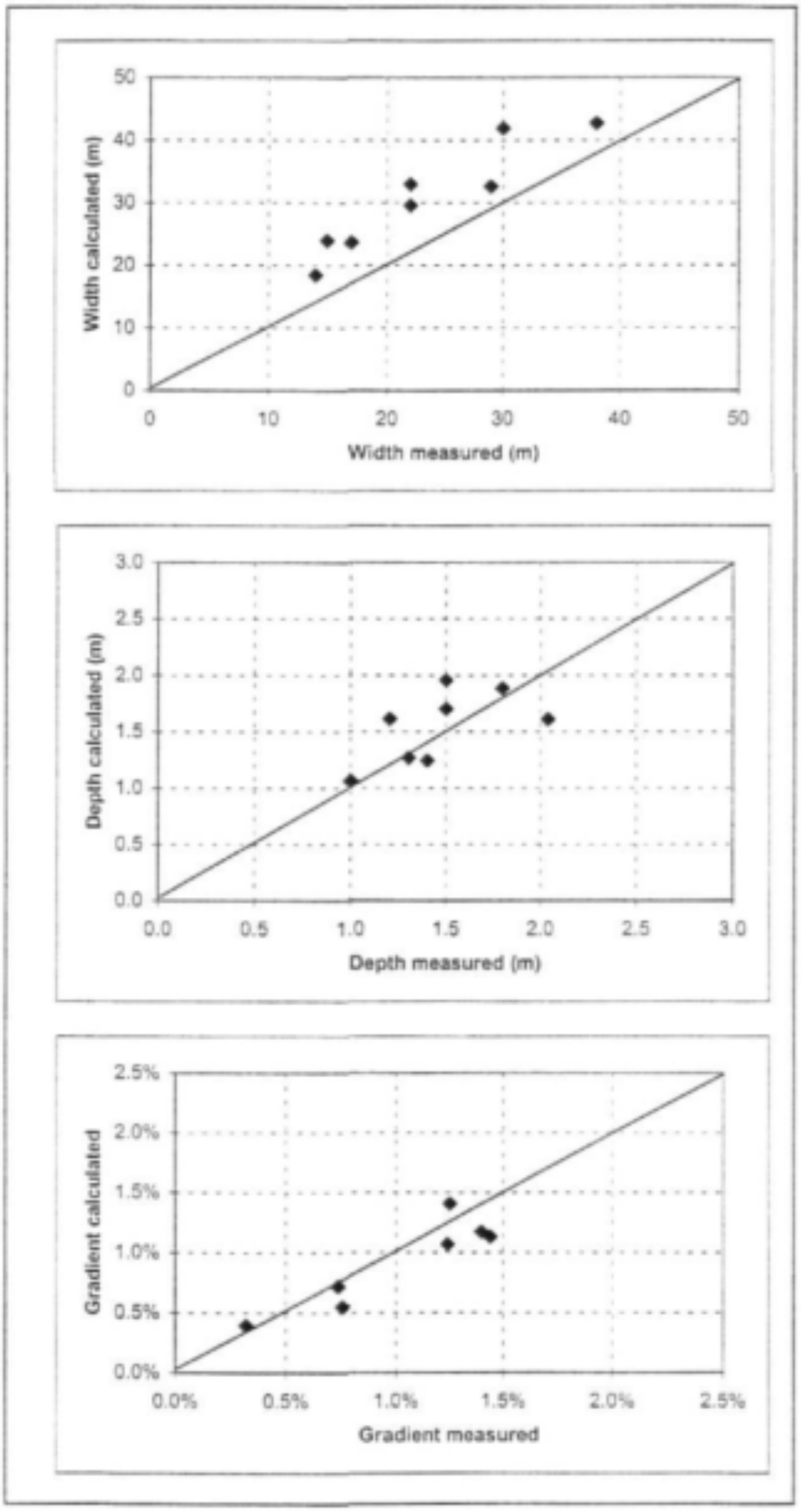


Figure 5.10: A comparison of the observed channel geometry with the channel geometry as predicted by Yalin's (1992) regime equations at a discharge equal to Q_c

5.4 Conclusion

In the first part of this Chapter, the morphological characteristics of cobble and boulder bed rivers in the Western Cape were addressed and it was shown that consistent relationships exist between channel geometry, catchment area (discharge) and bed form geometry.

A review of existing regime models for rivers with large sized bed particles revealed that none of these models provides a complete morphological description in terms of those attributes which are important for ecosystem functioning, viz. substrate characteristics, pool depths, the local gradients of riffles and rapids which affect turbulence and the spacing or frequency of bed forms. In order to predict the environmental impacts associated with a modified flow regime, an understanding of the relationships between the channel forming discharge and the ecologically relevant morphological attributes is required and a model was subsequently proposed for predicting the regime characteristics of cobble and boulder bed rivers. The model, which can be classified as a rational regime model, is based on the hypothesis that the formation of pools and riffles is essentially a mechanism of self-adjustment by the stream system towards obtaining dynamic equilibrium, i.e. at a characteristic discharge and bed particle size distribution, the river adjusts its width, average gradient, local gradient of the riffle or rapid, absolute roughness and flow depth until equilibrium exists, in terms of the power applied along the bed and the power required to suspend bed particles as well as in terms of momentum exchange between the accelerating water along the riffle and the slower moving water in the pool. This behaviour is comparable to the formation of bed forms in sand bed rivers, where flow resistance is increased in order to dissipate excess energy and to limit the scouring of sand from the river bed (Rooseboom and Le Grange, 2000).

With the aid of field data the model was verified in typical cobble and boulder bed rivers in the Western Cape, by calculating a characteristic discharge, which, in accordance with the hypothesis, is equivalent to the channel forming discharge. This discharge was then evaluated in terms of its hydrological significance, its ability to entrain bed particles and its relationship to bankfull discharge. It was found that

- the discharge corresponds to floods with a return period of between 1 and 3 years.
- at different locations along the bed profile, the shear velocity at this discharge consistently approximates the critical shear velocity for a certain particle size as a percentile value of the overall substrate size distribution within the reach ($\pm d_{95}$ in rapids or riffles, $\pm d_{84}$ at the crest and $\pm d_{35}$ in pools).

- based on indirect methods, the discharge shows good correlation with bankfull discharge.

The regime model which was developed defines the relationship between the channel forming discharge and channel morphology in cobble and boulder bed rivers and as such provide a methodology for predicting the long term impacts of changes in a river's flow regime on the development and characteristics of macro scale bed forms. However, cognisance should be taken of the fact that the relationship between discharge and channel form is a complex one and that the above relationships need to be further refined by addressing aspects such as the duration of discharge and the effects of sinuosity and sediment transport. Preferably this should include both field and laboratory experiments.

6. THE SCOURING OF SAND IN COBBLE BED RIVERS

6.1 Introduction

Whereas Chapter 5 addressed the morphological characteristics of cobble and boulder bed rivers in terms of their regime behaviour on a macro scale, this chapter is concerned with equilibrium conditions in these rivers at a much smaller scale. More specifically, the scouring of sand from the interstitial spaces between the cobbles is addressed.

In cobble bed rivers many aquatic species are dependent on the interstitial spaces between the cobbles for their survival. Salmonids, for example, use these spaces for laying their eggs while the spaces also provide habitat and sheltering for various benthic insects (Gordon *et al*., 1992). The accumulation of fine sediments in cobble bed rivers, which fill these interstitial spaces, can therefore have a detrimental effect on the whole aquatic ecosystem. Although natural phenomena such as catchment erosion after fires may lead to excessive sediment loads being introduced and deposited on cobble river beds, natural floods ensure the periodic removal thereof. The construction of a reservoir, however, leads to a change in flood peaks, flooding frequency as well as changes in the sediment transport capacity in the river channel downstream. Fine sands introduced into this part of the river system from the incremental catchment downstream of the reservoir, may therefore accumulate on parts of the river bed. In order to flush these unwanted fine sands from the interstitial spaces between the cobbles and gravels downstream of reservoirs, special reservoir releases known as flushing flows or sediment maintenance flows, may be specified (Wilcock *et al*., 1996).

The range of effective flushing flows is relatively narrow. Whereas the rate and efficiency of fine sand removal increase with discharge, so does the potential cost in the form of lost economic opportunity as the released water is lost for storage or power generation. The transport rate of larger sized sediments also increases 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). Finally, the scheduling of flushing flows is subject to uncertainty due to the complexity of flow and sediment transport patterns in cobble bed rivers. There is a clear need to specify flushing flows as accurately as possible, as relatively crude methods have often been used due to a lack of appropriate models. One method which is used is to specify a discharge with a certain return period (e.g., the two year peak flow), based on it having had the desired observed effect in other channels. Other methods are based on estimates of critical shear stress in mixed size sediments (Reiser *et al.*, 1989). These methods however, lack a fundamental theoretical basis which is needed for flushing flows to be specified in terms of time and discharge dependent relationships describing the depth of scour of fine sands from between cobbles. Ligon *et al.* (1995) and Kondolf and Wilcock (1996) noted that "the goals of flushing flows need to be stated in terms of measurable changes to the physical habitat rather than the abundance of organisms". In line with this philosophy, research was therefore undertaken in this project to develop a scour model which predicts the maximum depth of scour as well as the rate of scour of fine sands in a cobble bed.

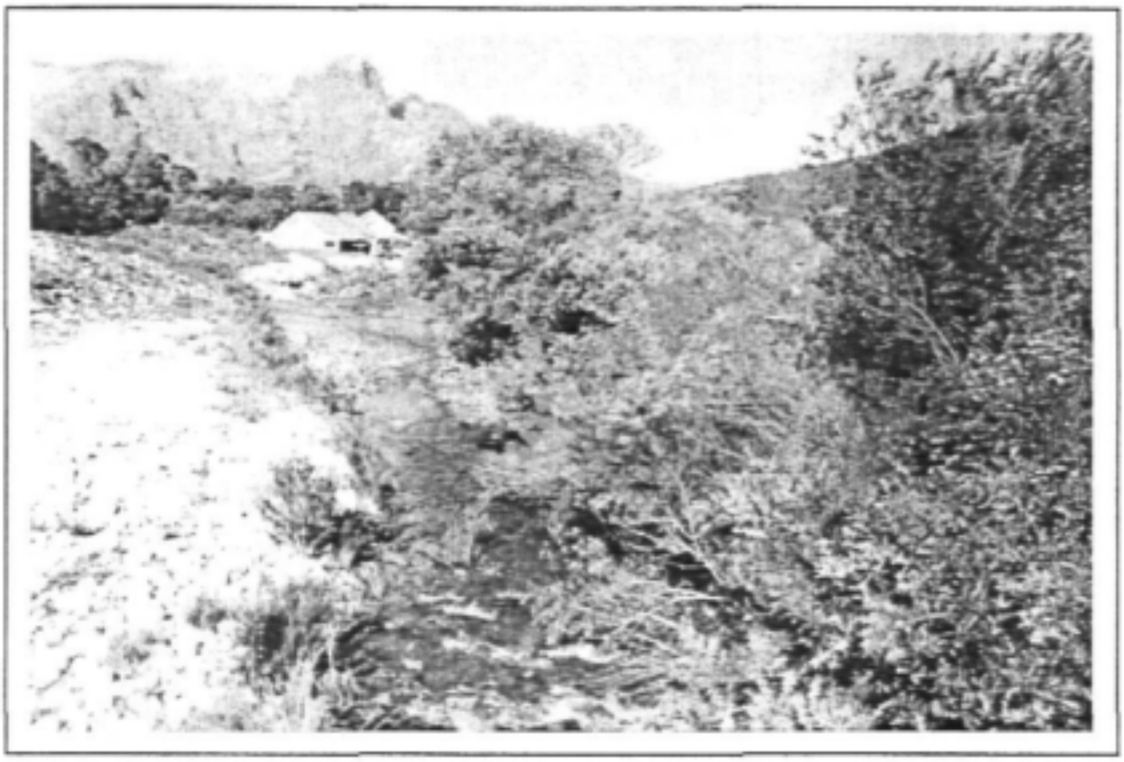


Figure 6.1 : Typical cobble bed river siltation (Wemmershoek River below dam)

6.2 Theoretical background

6.2.1 Sediment transport and the principle of least applied power

The law of conservation of power has been found to provide good insight into the sediment transport characteristics of streams. This law, which is defined in scalar terms and directly related to time, is a third derivative of Newton's second law together with the laws of conservation of energy and momentum (Rooseboom, 1974 ; 1998).

Rooseboom (1974) defined the law of conservation of power under conditions of steady, uniform flow as

$$\int_{y_0}^{D} \rho g s v \, dy = \int_{y_0}^{D} \tau \frac{dv}{dy} dy \qquad (6.1)$$

with ρ : fluid density (kg/m^3)

g : gravitational acceleration (m/s^2)

s : energy gradient ≈ channel gradient

v : velocity at distance y above the bed (m/s) ($\approx \frac{1}{\kappa}\sqrt{gDs}\ln\frac{y}{y_0}$)

D : flow depth (m)

y_0 : ≈ k/30 ; ordinate where the velocity is mathematically = 0 (m)

τ : shear stress at distance y above the bed (N/m^2)

k : absolute bed roughness (m)

κ : von Karman coefficient ($\approx \frac{1}{2\pi}$)

(The parameter ρgsv in equation 6.1 represents the amount of unit power made available by the flowing stream, whereas the parameter $\tau \frac{dv}{dy}$ represents the power applied per unit volume to maintain motion.)

Where alternative modes of flow exist, that mode of flow which requires the least amount of unit power will be followed and it therefore follows that fluid flowing over movable material would only transport the material, if it will result in a decrease in the amount of unit power being applied (Rooseboom, 1974; 1998). As the power applied along the bed of a river varies depending on whether laminar or turbulent flow conditions prevail at the bed, the critical condition for sediment movement also depends on whether the flow at the bed is laminar or turbulent.

Under conditions of laminar or smooth turbulent flow, Rooseboom (1974) showed that the unit stream power applied along the bed equals

$$\frac{(\rho g s D)^2}{\rho \nu} \qquad (6.2)$$

with ν : kinematic viscosity (m^2/s).

The applied power required per unit volume to suspend a particle with density ρ_s and settling velocity V_{ss} in a fluid with density ρ, equals

$$(\rho_s-\rho)g\,V_{ss} \tag{6.3}$$

Stokes' law (Graf, 1971), defines the settling velocity of a particle with diameter d under viscous conditions as

$$(V_{ss})_{LAM}\ \alpha\ d^2 g\frac{\rho_s-\rho}{\rho\nu} \tag{6.4}$$

The critical condition for the movement of sediment particles is reached when the power applied along the bed exceeds the power required to suspend the sediment particles. In laminar or smooth turbulent flow therefore, from equations 6.2, 6.3 and 6.4, a relationship defining the threshold for sediment transport under viscous conditions can be defined. This relationship, calibrated with data by Grass (1970) and Yang (1973), was found to be:

$$\frac{\sqrt{gDs}}{V_{ss}}=\frac{1.6}{\dfrac{\sqrt{gDs}}{\nu}.d} \tag{6.5}$$

for values of $\frac{\sqrt{gDs}.d}{\nu} < 13$, i.e. with smooth turbulent or completely laminar flow over a smooth bed (Rooseboom, 1974 ; 1998).

Under conditions of rough, turbulent flow, Rooseboom (1974; 1998) showed that the unit applied power near the bed (at y_0), where $D-y_0 \approx D$, is

$$\left(\tau\frac{dv}{dy}\right)_0 \approx \frac{30\rho gsD\sqrt{2\pi gsD}}{d} \tag{6.6}$$

Furthermore, under conditions of turbulent flow, the settling velocity as expressed by Graf (1971) equals

$$(V_{ss})_{TURB}=\sqrt{\frac{4(\rho_s-\rho)gd}{3\rho C_d}} \tag{6.7}$$

with C_d : drag coefficient (assumed constant for larger diameters).

From equations 6.3, 6.6 and 6.7 the critical condition for the movement of sediment along an even bed in rough turbulent flow can thus be defined by

$$\frac{\sqrt{gDs}}{V_*} = \text{Constant} \qquad (6.8)$$

This relationship was calibrated with measured data from Yang (1973) and the value of the constant was found to be 0,12 for values of $\frac{\sqrt{gDs}.d}{\nu} > 13$ (Rooseboom, 1974 ; 1998).

6.2.2 Dynamic equilibrium on a sand streambed

Equation 6.6, which represents the amount of stream power applied along a bed under conditions of rough turbulent flow, can also be written as:

$$\left(\tau\frac{dv}{dy}\right)_0 = \frac{14{,}8\rho gsD\sqrt{2\pi gsD}}{R_0} \qquad (6.9)$$

with $\left(\tau\frac{dv}{dy}\right)_0$: unit applied power near the bed

R_0 : ≈ d/2 ; the radius of a turbulent eddy next to the bed (m).

Based on the concept of minimum applied power, equation 6.9 therefore suggests that once sediment is being transported, a further reduction in the amount of unit turbulent stream power applied along an alluvial bed is possible by means of (Rooseboom, 1974) :

- The formation of a pseudo-viscous zone of high concentration suspension along the bed (increasing R_0)
- The formation of bedforms i.e. ripples, dunes etc. (increasing R_0)
- Creating a meandering course (decreasing slope)

Furthermore, it can be shown (Rooseboom, 1992) that the sediment concentration at any level within a stream is directly proportional to (applied power)^z and subsequently that the sediment carrying capacity of a stream is proportional to (applied power along the bed)^z , with z defined as

$$z = \frac{5\sqrt{2\pi}\,.V_m}{6\sqrt{gDs}} \tag{6.10}$$

It therefore follows that as an alluvial stream reduces the amount of unit stream power applied along the bed by deformation of the bed, the stream is also in effect decreasing its sediment carrying capacity. This process continues until a condition is reached where the size of the boundary eddies that fit in with the bedforms become so large that the average rate of deposition of the particles is equal to the average rate of re-suspension of the particles. When this point is reached, the stream is in a condition of steady state sediment transport or dynamic equilibrium. Under conditions of equilibrium sediment transport, with particles on the bed being entrained and deposited at the same rate, critical hydraulic conditions must prevail at the bed where individual particles are continually passing across the movement threshold (Rooseboom and Le Grange, 2000). However, Rooseboom (1974) observed that it is not possible to have sand particles less than about 2 mm in diameter at rest under turbulent boundary conditions on an even bed, as the absolute roughness is too small to induce a turbulent boundary layer. It therefore follows that with dynamic equilibrium along a sand bed, laminar boundary conditions have to prevail at the bed. From equations 6.3 and 6.4, for laminar conditions along a smooth bed, the unit stream power required to suspend a particle of diameter d equals

$$\frac{(\rho_s - \rho)^2 g^2 d^2}{\rho \nu} \tag{6.11}$$

In a similar fashion, from equation 6.6, when turbulent flow conditions prevail along an even bed the unit stream power applied in maintaining motion along the bed is

$$\approx \frac{30\rho gsD\sqrt{2\pi gsD}}{k} \tag{6.12}$$

with k : absolute bed roughness (≈ particle diameter (d) with an even bed) (m).

As an even sand bed becomes deformed, the applied turbulent power at the bed is reduced until equilibrium is reached. At the point of dynamic equilibrium therefore, critical conditions exist at and below the interface between the thin laminar boundary layer along the bed and the turbulent eddies above. The applied turbulent unit stream power at the bed, expressed in terms of the absolute bed roughness, must therefore be proportional to the unit power which is required to bring particles into suspension under laminar conditions (Rooseboom and Le Grange, 2000). Therefore, from equations 6.11 and 6.12

$$\frac{30\rho gsD\sqrt{2\pi gsD}}{k} \alpha \frac{(\rho_s - \rho)^2 g^2 d^2}{\rho v}$$

which can be written as

$$\frac{(30\sqrt{2\pi}\, v)(\rho gsD)^2}{(\sqrt{gDs}\, k)(\rho v)} = (\text{constant}) \frac{(\rho_s - \rho)^2 g^2 d^2}{\rho v}$$

and which leads to

$$\frac{\sqrt{gDs}}{V_{ss}} = \left[\frac{\sqrt{gDs}\,.k}{\sqrt{2\pi}.v}\right]^{1/2} (\text{constant}) \left[\frac{v}{\sqrt{gDs}\,.d}\right] \qquad (6.13)$$

Equation 6.13 represents the condition of dynamic equilibrium in a sand bed river and defines the relationship between absolute roughness and bed deformation under steady state sediment transport conditions. Comparison of equation 6.13, describing dynamic equilibrium in an alluvial river with bedforms, with equation 6.5, representing critical conditions in laminar flow, reveals an additional parameter of $\left[\frac{\sqrt{gDs}\,.k}{\sqrt{2\pi}\,.v}\right]^{1/2}$ in equation 6.13. Rooseboom and Le Grange (2000) calibrated equation 6.13 with available data on sand bed deformation under conditions of dynamic equilibrium. Their findings confirmed that, contrary to conventional wisdom, a laminar boundary layer comes into play at equilibrium conditions in a deformed sand bed river. They also concluded that the parameter of $\left[\frac{\sqrt{gDs}\,.k}{\sqrt{2\pi}\,.v}\right]^{1/2}$, referred to as delta ($\Delta$), reflects the decrease in transporting capacity due to deformation of the bed with k, the absolute roughness, reflecting the size of the boundary eddies that fit in with the changing bed forms.

Since scouring of fine sediments along a cobble-covered river bed is associated with changes in absolute bed roughness as the cobbles become exposed during scouring, it is hypothesized that *the process of fine sediment scouring in a cobble bed river and the associated change in absolute bed roughness is similar to the process of bed deformation in a sand bed river, except for the fact that the cobbles will limit the extent of bed deformation.* For a cobble bed, the relationship that exists between the sand particle characteristics and the maximum scour depth, should therefore be similar to the relationship that exists between absolute roughness (as represented by delta) and particle characteristics under conditions of dynamic equilibrium on a deformed sand bed river, provided that allowance is made for the presence of the cobbles. In order to evaluate this hypothesis, laboratory studies were undertaken.

6.3 Development of a sand scour model for cobble bed rivers

6.3.1 Experimental procedure

During the laboratory experiments, various combinations of sand and cobble sizes were used and relationships developed between applied power, particle characteristics, the rate of scour and the maximum scour depth. Tests were performed in a horizontal flume of 1,0 m width and 40 m length in the hydraulics laboratory of the Department of Civil Engineering of the University of Stellenbosch. Cobbles were collected from rivers and sorted with a gravelometer. Two to three layers of uniform, spherical cobbles were arranged in a closely packed pattern in order to create an artificial cobble bed. The length of the cobble bed was approximately 2,4 m and provided a sufficient area in which to investigate the scouring effect. The cobbles were then completely covered with sand of a fairly uniform grading. At the upstream side of the cobble bed, a transition of gravel and smaller cobbles was constructed to allow full development of the turbulent flow profile. Flow depths were controlled with an adjustable weir at the downstream end of the flume. Average velocities above the cobble bed were measured with an Ott-meter. The laboratory setup is shown diagrammatically in Figure 6.2.

After preparation of the sand-covered cobble bed, the following basic procedure was followed:

- With the adjustable downstream weir controlling the water level in the flume, water was allowed to fill the flume very slowly in such a way that no sand movement took place along the cobble bed.
- The water supply to the flume was slowly increased until the desired discharge was obtained. The discharge was calculated from velocity and depth measurements above the cobble bed as well as from the level at the downstream weir. A large enough depth was maintained above the cobble bed to ensure that no sand movement took place.
- The adjustable weir was then rapidly lowered until the desired water depth above the experimental cobble bed area was reached. This represented the start of the experiment.

- At pre-determined positions along the bed, the level of the sand (depth of scour) was measured as the experiment progressed until no further change in the scour level could be observed.

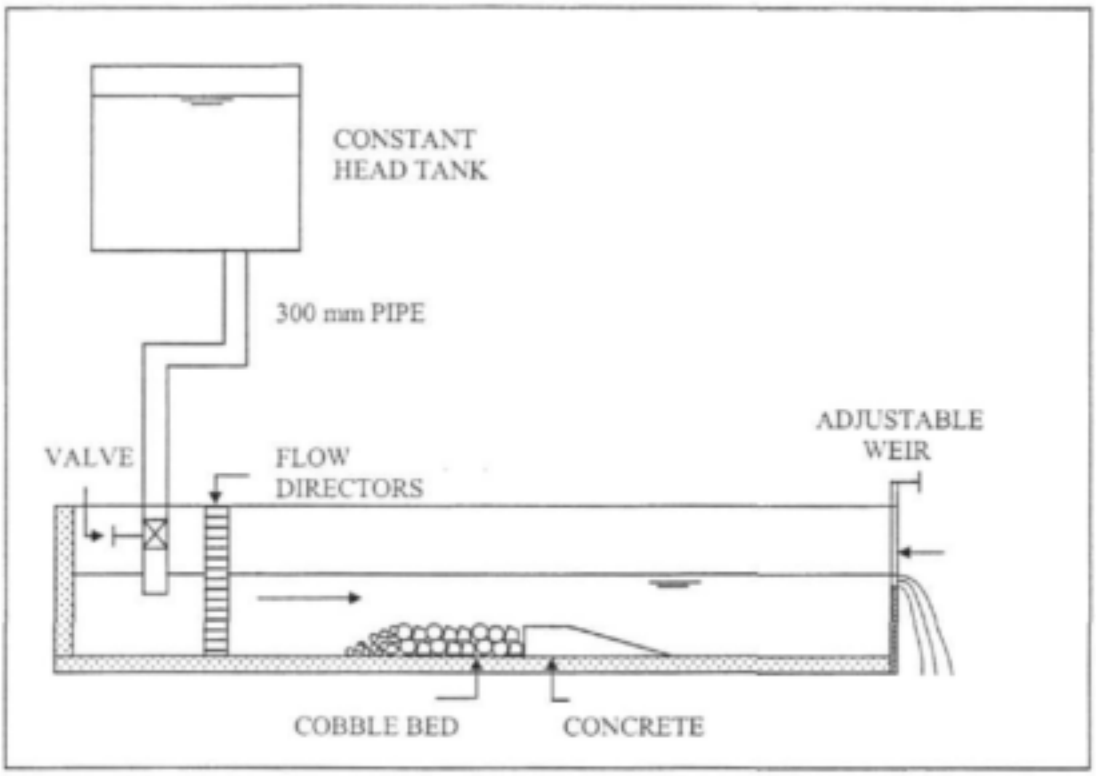


Figure 6.2 : Laboratory setup

In total, 64 experiments were completed. Different sand-cobble combinations, which represented a broad spectrum of cobble and sand particle sizes, were tested (see Table 6.1.)

Experimental setup	Median sand diameter (mm)	Cobble diameter (mm)
I	0,22	60
II	0,83	60
III	0,22	71
IV	0,54	80
V	0,54	130
VI	0,22	130

Table 6.1 : Sand-cobble combinations

The difference in energy and associated water levels between the upstream and downstream sections of the cobble bed reach was too small to measure accurately in order to determine the energy gradient. As the flow depth above the cobble bed was controlled by the downstream weir, the flow in the flume could be classified as gradually varied. Based on the procedure for calculating the energy slope under conditions of gradually varied flow (direct- and standard step methods), the Chézy formula was used to calculate the energy slope above the cobble bed area from the measured average velocity. The scour depth beneath the top of the cobbles was used to represent the absolute roughness (k) in the Chézy equation. Due to the difference in resistance between the cobble bed of the flume and the glass sidewalls, it was assumed that the total flow resistance would be affected only slightly by the sidewalls. The flow was assumed to be two-dimensional and the hydraulic radius in the Chézy equation was substituted with the flow depth above the cobble bed. In order to limit the uncertainty associated with large-scale roughness, the ratio of flow depth to absolute roughness was maintained at values above three (Chow, 1959). (Appendix F lists the experimental results.) The outcome of a typical scour experiment is shown in Figure 6.3.

6.3.2 Laminar boundary conditions

In order to gain insight into the hydraulic conditions that exist at the bed when the maximum level of sand scour is reached in a cobble bed, the laboratory data was analyzed in terms of the parameters $\frac{\sqrt{gDs}}{V_{ss}}$ and $\frac{\sqrt{gDs}\,.d}{\nu}$. (As already shown, the threshold condition for both laminar and turbulent boundary conditions may be defined in terms of these parameters.) The maximum scour depth reached below the cobble crests during each experiment, was used to represent the absolute roughness value (k) for calculation of the energy slope in the above parameters, while V_{ss} represents the settling velocity of the sand particles (diameter d) under laminar conditions. Figure 6.4 shows that scour data with similar values of Δ display the same pattern as that displayed by the incipient motion curve (Liu, 1957; Rooseboom, 1974) for particles smaller than 2 mm on an even bed with laminar boundary layer conditions. In line with Rooseboom and Le Grange's findings, Figure 6.4 therefore indicates that, in correspondence with dynamic equilibrium in a sand bed river, the condition of maximum scour depth in a cobble bed goes hand in hand with the formation of a laminar sublayer below the turbulent eddies that fit in with the shapes of the exposed cobbles.

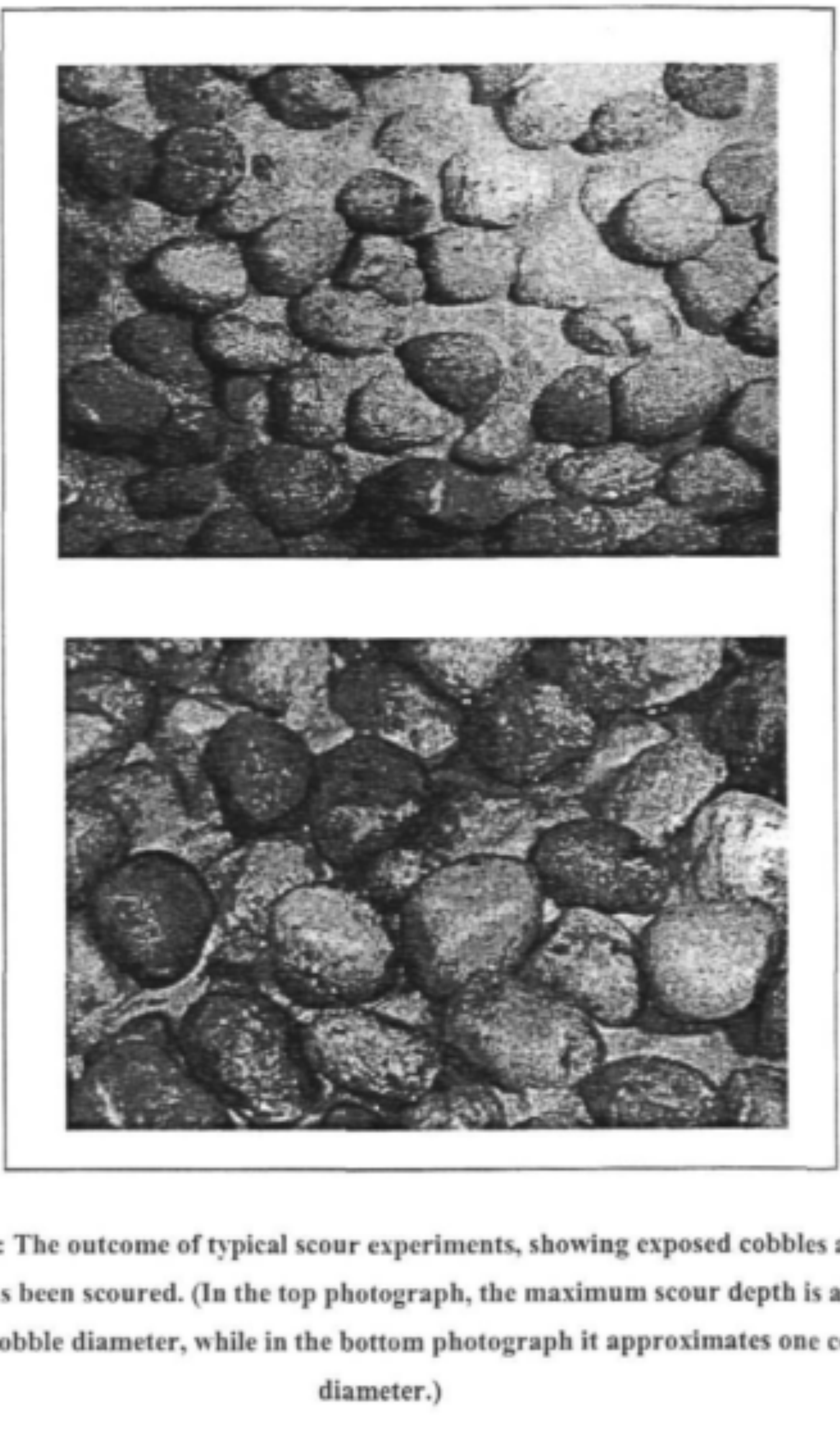


Figure 6.3 : The outcome of typical scour experiments, showing exposed cobbles after the sand has been scoured. (In the top photograph, the maximum scour depth is about half of the cobble diameter, while in the bottom photograph it approximates one cobble diameter.)

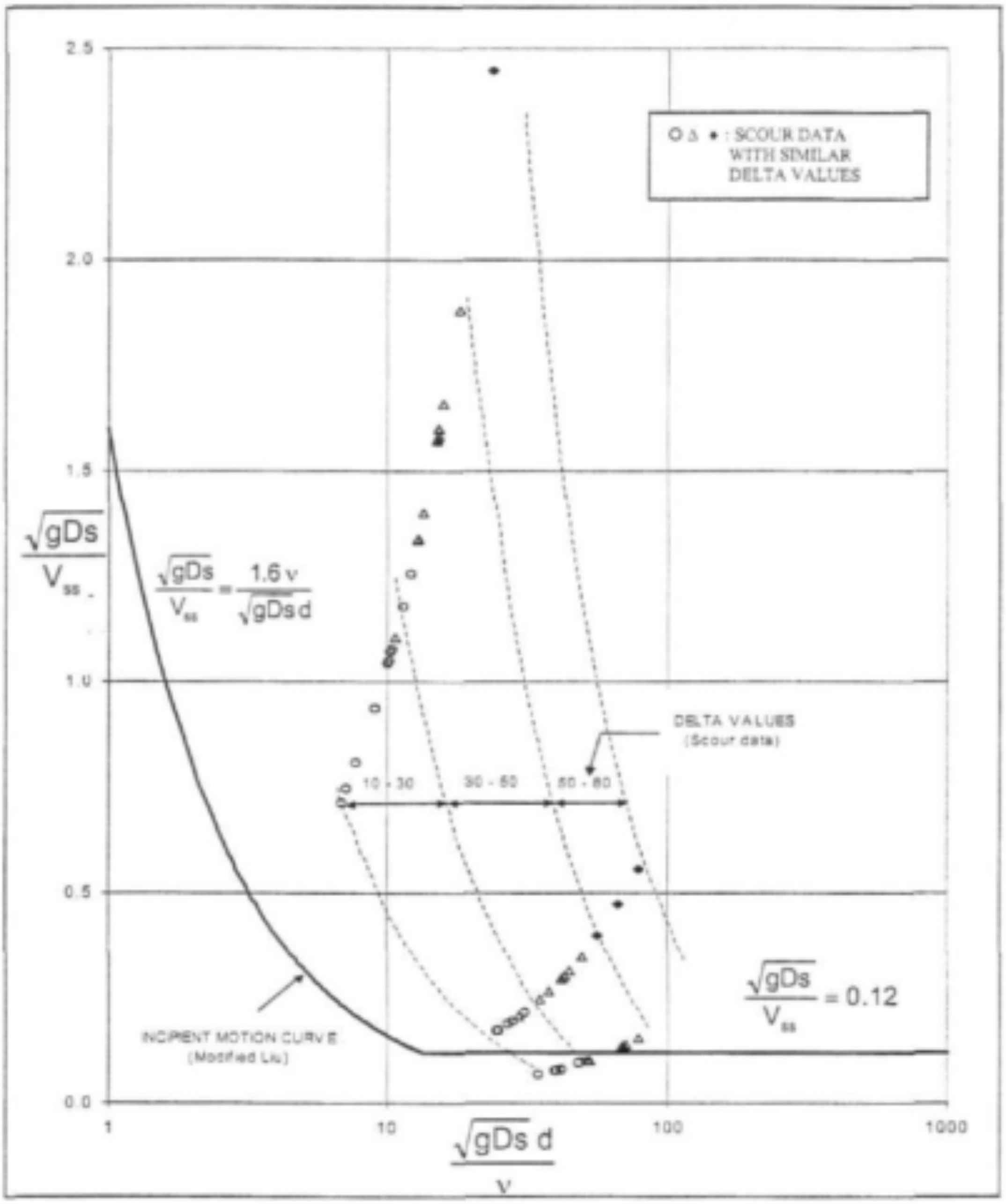


Figure 6.4 : Scour data in relation to critical conditions for cohesionless sediment particles

6.3.3 The maximum depth of scour

The theory of dynamic equilibrium enabled Rooseboom and Le Grange (1994) to represent the full spectrum of bed conditions in a sand bed river, from lower regime to upper regime, within a single system. Figure 6.5 displays the typical progression of equilibrium conditions in a sand bed river for three different particle diameters. It indicates that for any particular sand diameter, as $\frac{\sqrt{gDs}}{V_{ss}}$ increases, equilibrium with lower regime bedforms goes hand in hand with increasing k or $\left[\frac{\sqrt{gDs}\ .k}{\sqrt{2\pi}\ .v}\right]^{1/2}$ values and laminar boundary conditions. This continues until a sharp turning point is reached when the boundary conditions below the turbulent eddies switch to being turbulent. The bed becomes unstable and while $\frac{\sqrt{gDs}}{V_{ss}}$ values remain constant, k-values decrease dramatically until a new turning point is reached, from where upper regime bedforms develop and laminar boundary conditions again dominate.

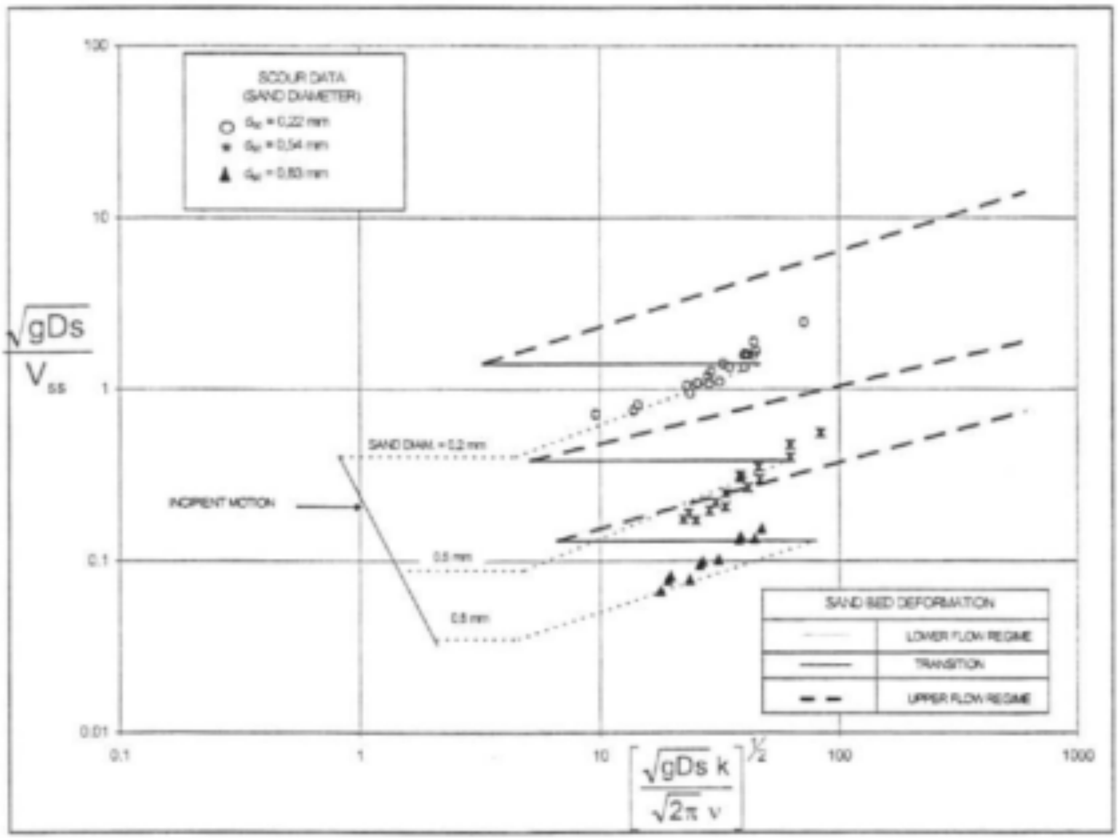


Figure 6.5 : Delta values during dynamic equilibrium in a sand bed river with the new cobble bed scour data superimposed

If the results of the scour experiments are superimposed in Figure 6.5, it is clear that for a particular sand diameter, as the value of $\frac{\sqrt{gDs}}{V_{ss}}$ increases, the maximum scour depth that is reached (represented by Δ) increases in similar fashion to the progression of equilibrium conditions and associated bedforms in a sand bed river. In addition, Figure 6.5 shows that unlke sand bed rivers, where transition from lower to upper regime bedforms occur as $\frac{\sqrt{gDs}}{V_{ss}}$ increases (as indicated by the horizontal, solid lines), no transition occurs in the case of the 0.22 mm and 0.54 mm sand. This is expected as the "bedforms" in a cobble bed are fixed by the exposed cobbles, which cannot be washed away. Figure 6.5 therefore confirms the hypothesis that the hydraulic conditions during sand scouring along a cobble bed river are comparable to those that prevail under conditions of dynamic equilibrium in a sand bed river.

The next diagram (Figure 6.6), which was developed by Rooseboom and LeGrange (2000), provides a complete averaged picture of the relationship between absolute roughness and particle characteristics under different flow conditions in an alluvial sand bed river. Again, if the results of the scour experiments are superimposed in Figure 6.6, it proves that not only do similar relationships exist between the maximum scour depth in a cobble bed and dynamic equilibrium conditions in a sand bed river as represented by Δ, but that the Δ-values themselves are of the *same order of magnitude* ; even though the definitions differ. The observed Δ values can thus be extrapolated according to the pattern for sand bed rivers, for use in calculating the discharges which are required to scour sand from cobble beds down to certain depths.

6.3.4 The rate of scour

As a flushing flow management programme should include the magnitude and duration of flows, it is imperative that apart from predicting the maximum scour depth, a scour model should also be time-related. In order to define the rate of scour on a cobble bed, a relationship needs to be established between the stream's ability to entrain sand particles from the interstitial spaces between the cobbles and the effort needed to entrain the particles. In terms of stream power principles, this can be interpreted as the ratio $\left[\frac{\text{Unit power applied along bed}}{\text{Unit power required to suspend particles}}\right]$, which reflects the ratio of the stream's capacity to suspend bed particles relative to the minimum power required to keep the particles in suspension (Rooseboom and Le Grange, 2000) and should serve as an indicator of the rate of scour. On the assumption that laminar boundary conditions only come fully into play at the point when the maximum scour depth is reached and not during the scour process, turbulent boundary conditions can be assumed to exist during the progression of scour. From equations 6.3 and 6.9 therefore, the above ratio is directly proportional to

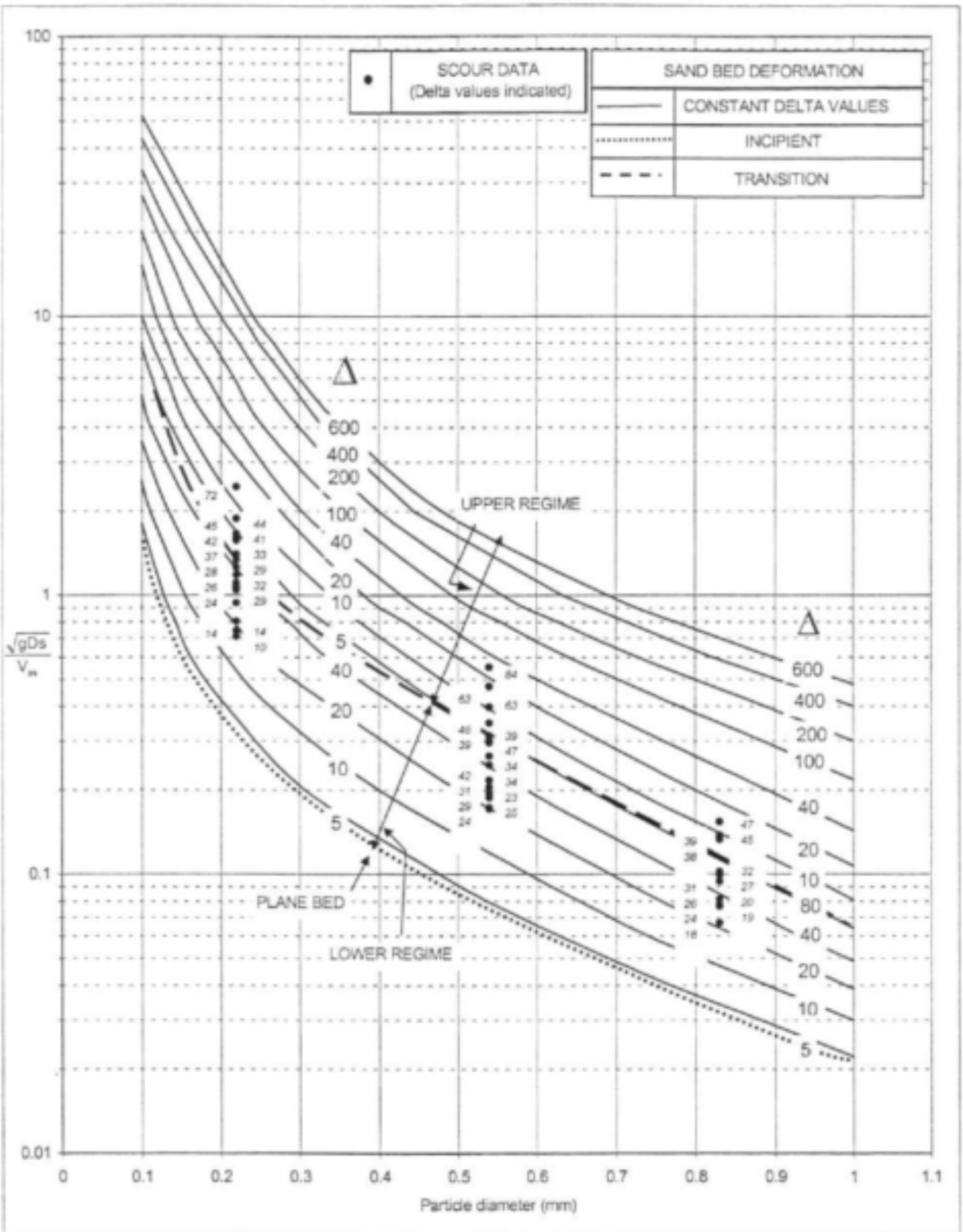


Figure 6.6 : Δ-values and bedforms in a sand bed river with the new cobble bed scour data superimposed

$$\frac{\left(\tau \frac{dv}{dy}\right)_0}{V_{ss}} \qquad (6.14)$$

with $\left(\tau \frac{dv}{dy}\right)_0$ and V_{ss} respectively representing the applied power at the bed and the settling velocity under turbulent conditions. If this parameter is compared with the scour rate, as measured during the laboratory experiments, Figure 6.7 shows that a definite trend exists, albeit with a large degree of scatter.

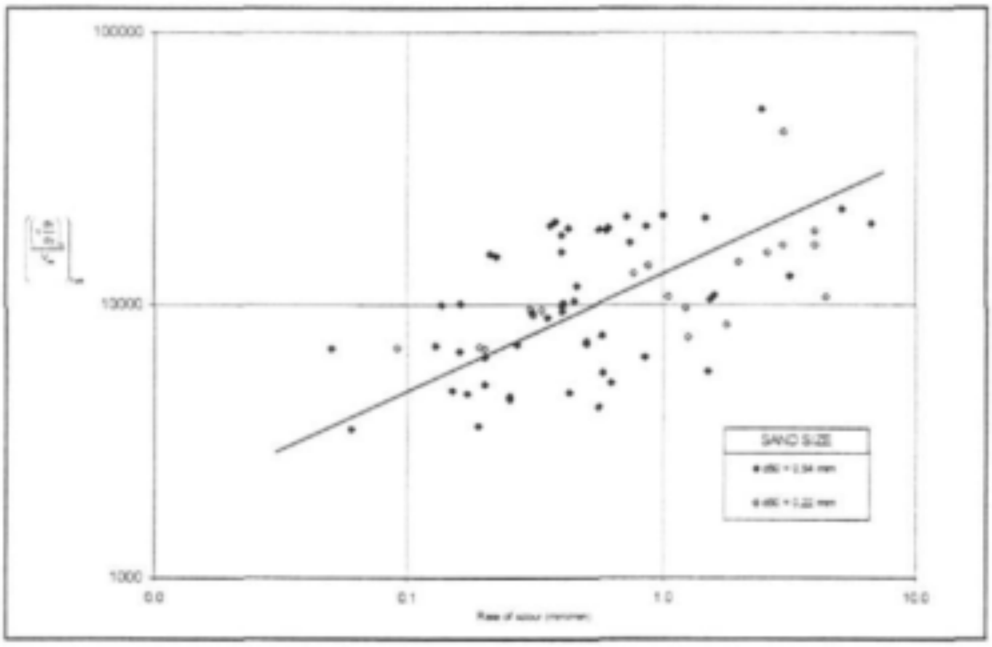


Figure 6.7 : The relationship between rate of scour, turbulent applied power and turbulent settling velocity

(Regression equation : $\text{Scourrate(mm/min)} = \left(\frac{\left(\tau\, dv/dy\right)_0}{V_{ss}} - 2414\right) / 3840$; $r^2 = 0.33$)

6.4 Conclusions

A scour model has been developed, which predicts the maximum depth of scour as well as the rate of scour of fine sands in a cobble bed. The maximum scour depth represents the level below the top of the cobbles at which no further scour is observed, while the rate of scour refers to the progression of the scour level below the top of the cobbles. The model has been developed from a model defining the condition of dynamic equilibrium for steady state sediment transport in a sand bed river. With the aid of physical model studies, distinct relationships were derived between the absolute roughness or maximum depth of scour, represented by Δ, sand particle characteristics and the relative applied power ($\frac{\sqrt{gDs}}{V_{ss}}$). The findings are based on average conditions within the cobble bed area. Because of the uncertainties involved when scour depths become large, the experiments only focused on scour depths of up to one cobble diameter. Cognisance should be taken of the fact that the experiments were conducted under clear water conditions. In practice therefore, the results are only applicable to the upstream section of a sand-covered cobbled bed where the flushing water is still relatively clear and void of suspended sediment. Although the experiments were conducted under clear water conditions, the results indicate similar patterns for the clear water experiments and for equilibrium sediment transport in sand bed rivers. This suggests that in both cases the equilibrium condition is characterized by particles at the bed constantly crossing the threshold between deposition and entrainment.

Table 6.1 indicates that different cobble sizes were used in combination with the 0,22mm and 0,54mm sand. It was expected that the different cobble diameters would affect the sizes of the boundary eddies, which in turn determine the power being applied at the bed and eventually the maximum scour depth. However the results indicate that the effect of cobble size is small and that cobble diameter as such does not seem to play a significant role in the size of the boundary eddies. It rather seems that the size of these eddies is primarily a function of the scour depth or absolute roughness, which suggests that the laboratory results can be extrapolated to represent larger scour depths associated with larger cobbles. This is further confirmed by Figure 6.5, which indicates an almost linear increase in the value of delta with increasing values of $\frac{\sqrt{gDs}}{V_{ss}}$.

Finally, based on the experimental results, a diagram was calibrated which represents the relationship between the absolute bed roughness or maximum scour depth as represented by Δ and particle characteristics under different flow regimes in a cobble bed (Figure 6.8). It shows that the Δ-values typically range from about 10 to 80 for the range of cobble and sand diameters that were tested. Larger cobbles would lead to larger scour depths and higher Δ-values at higher values of $\frac{\sqrt{gDs}}{V_{ss}}$.

It is recommended that further research, which should include field experiments, must concentrate on the effects of :

- absolute cobble sizes
- non-uniform cobble-sized beds
- steady state sediment transport conditions

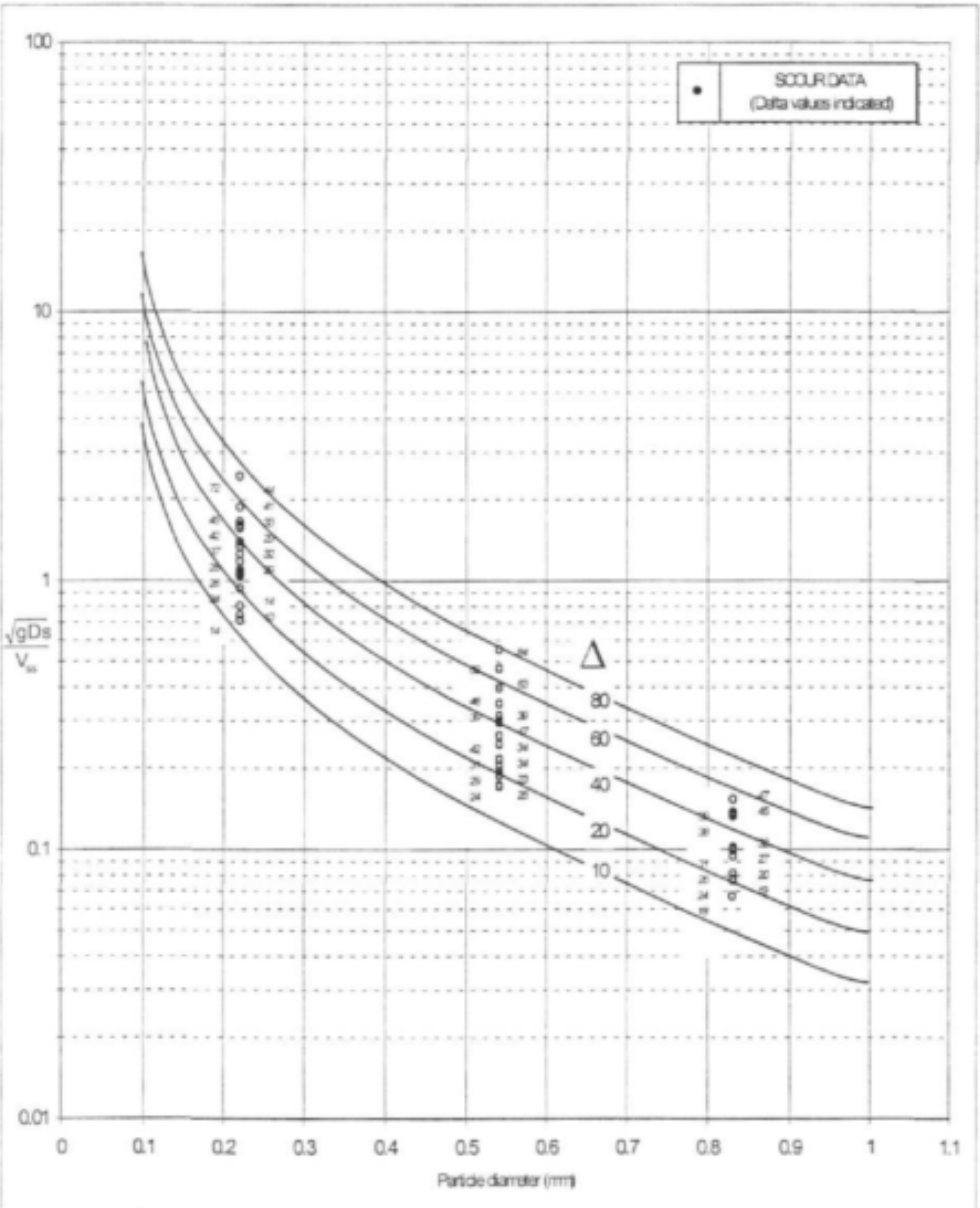


Figure 6.8 : Maximum scour depth in a cobble bed (clear water conditions)

III. ENVIRONMENTALLY SIGNIFICANT HYDRAULIC CHARACTERISTICS OF COBBLE AND BOULDER BED RIVERS IN THE WESTERN CAPE

7. STAGE DISCHARGE RELATIONSHIPS

7.1 Introduction

Central to the Environmental Flow Assessment process is the relationship between stage (flow depth) and discharge within the river channel. This relationship is used to translate flow depths or water levels, as indicated by the various specialists on the IFR team e.g. the botanist, zoologist, geomorphologist, etc. into corresponding discharge values. Furthermore, such a relationship is required for determining sediment transport characteristics or for predicting how the physical (hydraulic) habitat changes in relation to discharge.

One method of defining stage discharge relationships is to calibrate rating curves, which define the relationship between flow depth and discharge as measured at specific sites within the study river. Another approach is by means of friction-based formulae, which relate the mean velocity of flow to the flow depth or hydraulic radius, the energy gradient and a resistance coefficient. In the case of small scale roughness, where the physical roughness elements are small relative to the flow depth, flow resistance may be attributed mainly to boundary resistance, in which case the conventional friction-based formulae are well-defined. However, due to the different hydraulic processes of flow resistance under conditions of large scale roughness, when the flow depth and the bed particles are of the same order of magnitude, the standard friction based equations become increasingly inaccurate. This is typically the case in cobble and boulder bed rivers, which are characterized by steep gradients and relatively low flow depths in relation to bed particle size. This part of the research therefore focuses on the development of a generally applicable methodology for calculating stage discharge relationships under conditions of large scale roughness in cobble and boulder bed rivers of the Western Cape.

7.2 The estimation of mean velocity under conditions of large scale roughness

The estimation of mean velocity within a river channel is commonly defined by means of friction-based formulae, which, under uniform flow conditions, relate the mean velocity of flow to the flow depth or hydraulic radius, the energy gradient and a resistance coefficient. These equations take the following general form:

$$V = c R^{a_x} s^{b_x} \tag{7.1}$$

with V : average velocity (m/s)

c : resistance coefficient

R : hydraulic radius (m)

s : energy gradient ≈ channel gradient

a_x : constant

b_x : constant

The resistance coefficient in equation 7.1 depends upon various factors, viz. surface roughness, vegetation, channel irregularities and alignment, silting and scouring, channel size and shape, obstruction to flow and the relative roughness (Chow, 1959). The significance of these factors varies widely depending upon the character of the stream. For conditions of small scale roughness, where the physical roughness elements are small relative to the flow depth, flow resistance may be attributed mainly to surface drag on the channel boundary (boundary or skin resistance), for which case various forms of equation 7.1 have been developed based on a variety of empirical, semi-empirical and theoretical considerations. Examples are the Manning and Chézy equations, which are originally empirical in nature, and the Darcy Weisbach equation, which is partially based on theoretical boundary layer considerations and which defines the resistance coefficient by a semi-logarithmic function of the ratio of flow depth to a characteristic particle size on the boundary (Keulegan, 1938; Schlichting, 1979) expressed as

$$\sqrt{\frac{8}{f}} = a_2 + b_2 \log \frac{D}{d_x} \tag{7.2}$$

with f : Darcy Weisbach resistance coefficient

d_x : characteristic particle size (m)

D : flow depth (m)

As the relative roughness increases and the bed particles and flow depth become of the same order of magnitude, boundary resistance becomes less dominant, while form drag around the individual particles composing the channel bed and disturbance of the free water surface become more significant (Bathurst, 1985). Consequently, due to the different hydraulic mechanisms of flow resistance under conditions of large-scale roughness, the conventional friction based equations become increasingly inaccurate as they underestimate channel resistance significantly – by up to 100% according to Bathurst (1985). For this reason, Chow (1959) also recommends that the standard resistance coefficients only be used when the relative roughness is less than 0.3. Similarly, Bathurst *et al.* (1981) distinguishes between small-, intermediate- and large scale roughness (Table 7.1), with the understanding that the conventional resistance coefficients are only valid for the condition of small scale roughness.

Roughness scale	**Relative submergence**	
Small scale	$\frac{D}{d_{50}} > 7.5$	$\frac{D}{d_{84}} > 4$
Intermediate scale	$2 < \frac{D}{d_{50}} < 7.5$	$1.2 < \frac{D}{d_{84}} < 4$
Large scale	$\frac{D}{d_{50}} < 2$	$\frac{D}{d_{84}} < 1.2$

Table 7.1: Roughness scales

Generally, two approaches may be followed to estimate flow resistance under conditions of large scale roughness. The first approach involves empirical and semi-empirical resistance equations, which relate the resistance coefficient to the relative submergence, channel shape or other physical channel parameters. Alternatively, theoretically, process based resistance equations may be derived, which attempt to quantify flow resistance in terms of the resistance processes which dominate under conditions of large scale roughness.

7.3 Empirical and semi-empirical large scale roughness resistance equations

Numerous empirical and semi-empirical equations, which define flow resistance under conditions of large and intermediate scale roughness, have been developed. Most of these define resistance in terms of the dimensionless Darcy Weisbach friction factor, which is then used to calculate the mean velocity under the assumption of uniform flow. In general, these equations are of the same form and can be classified into two broad categories, viz.

- non-dimensional power equations:

$$\frac{1}{\sqrt{f}} = a_3 \left(\frac{R}{d_x} \right)^{a_3} \qquad (7.3)$$

- non-dimensional semi-logarithmic equations:

$$\frac{1}{\sqrt{f}} = a_4 \log\left(\frac{R}{d_x}\right) + b_4 \qquad (7.4)$$

(Equation 7.4 is essentially a modification of equation 7.2, the semi-logarithmic resistance equation derived from boundary layer theory.)

Table 7.2 lists typical large and intermediate scale roughness equations from literature. These equations, which were calibrated with data from gravel, cobble or boulder bed rivers clearly display the inverse relationship between flow resistance and relative submergence, i.e. the value of the resistance coefficient increases as the relative submergence decreases.

Reference	Equation	Particle d_{50} range	Relative submergence
	Non-dimensional power equations		
7.5 Charlton et al.(1978)	$\sqrt{1/f} = 1.27\,(D/d_{90})^{0.23}$	40 – 220 mm	-
7.6 Bray (1979)	$\sqrt{1/f} = 1.36\,(D/d_{50})^{0.281}$	-	3 – 150
7.7 Griffiths (1981)	$\sqrt{1/f} = 1.33\,(R/d_{50})^{0.287}$	15 –301 mm	2 – 200
	Non-dimensional semi-logarithmic equations		
7.8 Limerinos (1970)	$\sqrt{1/f} = 2.03\,\log\,(R/d_{50}) + 0.35$	-	-
7.9 Charlton et al (1978)	$\sqrt{1/f} = 1.94\log((D+d_{84})/d_{84}) + 0.78$	40 – 220 mm	-
7.10 Bray (1979)	$\sqrt{1/f} = 2.36\,\log\,(D/d_{50}) + 0.248$	-	3 –150
7.11 Griffiths (1981)	$\sqrt{1/f} = 1.98\,\log\,(R/d_{50}) + 0.76$	15 – 301 mm	2 –200
7.12 Hey (1979)	$\sqrt{1/f} = 2.03\,\log\,((aR)/3.5d_{84})$	50 – 250 mm	0.6 – 20
7.13 Bathurst (1985)	$\sqrt{8/f} = 5.62\,\log\,(D/d_{84}) + 4$	273 mm	0.5 – 10

Table 7.2 : Empirical and semi-empirical resistance equations

Various other types of empirical resistance equations have been developed for conditions of large and intermediate scale roughness (e.g. Thompson and Campbell, 1979; Ferro and Giordano, 1991; Pyle and Novak, 1981), which relate the resistance coefficient to additional physical parameters such as flow width, the standard deviation of bed particle size, effective roughness concentration, wetted frontal area of bed elements, etc. However, these equations become increasingly impractical for application in the field, due to the detailed input data which are required.

In general, the disadvantage of empirical and semi-empirical resistance equations is the fact that they tend to be site specific and consequently, great care has to be taken when applying these equations to conditions that are different to those under which they were calibrated (Bathurst, 1978; 1985). In order to develop a more generally applicable, theoretically based equation for the calculation of mean velocity under conditions of large scale roughness, a fundamental approach was therefore considered.

7.4 A fundamental approach towards the estimation of mean velocity under conditions of large scale roughness

A detailed literature survey confirmed that no process-based, flow resistance equations for conditions of large scale roughness exist. The only equation that attempts to describe the resistance processes which dominate under conditions of large and intermediate scale roughness, was developed by Bathurst *et al.* (1981). Assuming that the resistance to flow under conditions of large scale roughness is related mainly to the form drag of the roughness elements and their disposition in the channel, Bathurst accounted separately for the resistance effects related to Reynolds and Froude numbers, which determine the drag of individual elements, and the processes of roughness and channel geometry, and as such determined the combined effect of the roughness elements on the flow. Through the use of semi-empirical analyses, supported by extensive flume data, the following equation was derived:

$$\sqrt{\frac{8}{f}} = \left(\frac{0.28}{b_e}\mathrm{Fr}\right)^{\log(0.755/b_e)} 13.434\left(\frac{W_T}{d_{50}}\right)^{0.492} b_e^{\,1.025(W_{\alpha}/d_{50})^{0.118}}\left(\frac{A_w}{W_T D}\right) \qquad (7.14)$$

with Fr : Froude number

b_e : function of effective roughness concentration

W_T : flow width (m)

A_w : wetted roughness cross-sectional area (m^2)

Apart from the fact that this equation requires very detailed input data, which complicates its application, Thorne and Zevenbergen (1985) applied this equation to field conditions and found that it does not produce accurate estimates of flow resistance.

As part of this research, a simpler and generally applicable methodology for defining stage discharge relationships under conditions of large scale roughness was sought, which involved two approaches: Firstly, the principles of conservation of energy, momentum and power were applied to an ideal cobble bed river and, based on specific assumptions regarding the resistance processes that dominate under conditions of large scale roughness, equations for mean velocity were derived. Secondly, since velocity-depth relationships may be expressed in terms of the size of the boundary eddies (Rooseboom, 1974), the significance of the relationship between relative roughness, cobble diameter and the diameter of eddies which form next to the bed under conditions of large scale roughness, were investigated.

7.4.1 The principles of conservation of energy, momentum and power

Consider a river reach of length l and gradient S_0 as depicted in Figure 7.1, with the bed consisting of a single uniform layer of spherical cobbles of diameter d. Assume that the flow is uniform and let the number of cobbles within the reach along a streamline be equal to $\bar{n}$, while the total number of cobbles in the reach equals n.

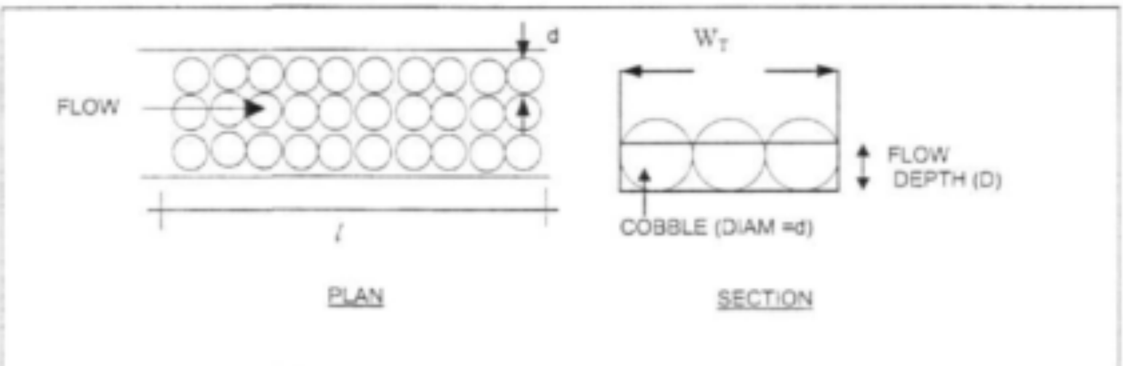


Figure 7.1: Schematic representation of ideal cobble bed river

i. The energy principle

Assume that during low flows in the river, energy losses can be ascribed mainly to transition losses which, in the Bernoulli equation, can be defined as:

$$h_l = C_l \frac{V^2}{2g} \qquad (7.15)$$

with h_l : transition loss (m)

C_l : transition loss coefficient

V : average flow velocity (m/s)

If equation 7.15 represents the transition loss due to one element, the transition losses along a streamline in the direction of flow, due to $\bar{n}$ elements, add up to

$$(h_t)_l = \bar{n}\, C_l \frac{V^2}{2g} \qquad (7.16)$$

However, for the ideal case being considered, $\bar{n} \approx l/d$ and therefore

$$(h_t)_l = \frac{l}{d}\, C_l \frac{V^2}{2g} \qquad (7.17)$$

The energy gradient over the reach (S_f), which is equal to the channel gradient (S_0) assuming uniform flow, equals $(h_t)_l / l$ and therefore, from equations 7.16 and 7.17, the average velocity (V) may be expressed as

$$V = \sqrt{\frac{2gdS_0}{C_l}} \qquad (7.18)$$

ii. The momentum principle

The momentum principle states that "the sum of all the external force components acting upon a body of fluid equals the difference between the sum of the momentum flux components of the outflows and the inflows" (Rooseboom, 1974). Under conditions of uniform flow, where the water depth and velocity remain constant, the momentum principle simplifies to a balance between the external forces in terms of the weight of the enclosed fluid and the force exerted on the enclosed fluid by the roughness elements.

Consider the section of river in Figure 7.1. Assume that the roughness elements act individually, generating a total resistance force based on the sum of their profile drags. (Profile drag is composed of form drag and skin friction, the latter being small compared with the former under conditions of large scale roughness.) From the momentum principle, the weight component of the body of water (with length l, width W_T and depth D) in the direction of flow, must equal the force exerted on the enclosed fluid by the roughness elements.

The weight component of the water body in the direction of flow may be expressed as

$$\rho\, g\, W_T\, l\, D\, S_0 \qquad (7.19)$$

while the drag force exerted by all the elements equals

$$(n)(0.5\ \rho\ C_d V^2 A_p) \tag{7.20}$$

with A_p : wetted frontal area of a roughness element (m^2)

C_d : drag coefficient

Equating equations 7.19 and 7.20 leads to the following equation for the average velocity:

$$V = \sqrt{\frac{2g}{C_d}}\sqrt{DS_0}\sqrt{\frac{\ell W_T}{nA_p}} \tag{7.21}$$

The ratio ($\frac{nA_p}{\ell W_T}$) in equation 7.21 is termed the "roughness concentration" and refers to the proportion of the total cross sectional flow area, which is occupied by roughness elements. For the ideal case being considered, and when the flow depth is less than the particle diameter, this ratio can be simplified as follows:

A_p may be approximated by the product of the ratio of flow depth to cobble diameter (D/d) and the frontal area of a cobble $\left(\frac{\pi d^2}{4}\right)$. Furthermore, from the plan view on Figure 7.1, (ℓW_T) may be approximated by $n\left(\frac{\pi d^2}{4}\right)$. The roughness concentration within the channel of length ℓ and width W_T, may thus be approximated by

$$\frac{n\left[\left(\frac{\pi d^2}{4}\right)\left(\frac{D}{d}\right)\right]}{n\left(\frac{\pi d^2}{4}\right)}$$

$$\approx \quad D/d \tag{7.22}$$

Equation 7.21 then becomes

$$V = \sqrt{\frac{2gdS_0}{C_d}} \tag{7.23}$$

iii. The principle of conservation of stream power

Again referring to Figure 7.1, consider a unit volume of water with mass m and average velocity V. The kinetic energy of this water element equals (½)mV^2. Assume that the kinetic energy loss per channel length equal to one cobble diameter (d) equals

$$C_k\,(½)\,m\,V^2 \qquad (7.24)$$

with C_k : kinetic energy loss coefficient

Let t represent the time it takes for the water element to move a distance equivalent to one cobble diameter. The rate of kinetic energy loss per length of channel equal to one cobble diameter then equals

$$[C_k\,(½)\,m\,V^2]\,/\,t \qquad (7.25)$$

However, t = V/d and for a unit volume of water with density ρ, m = ρ. Equation 7.25 therefore becomes

$$[C_k\,(½)\,\rho\,V^2]\,V\,/\,d \qquad (7.26)$$

which represents the power applied to maintain motion and, in line with the law of conservation of stream power, should equal the power made available by the decrease in potential energy of the element (Rooseboom, 1974). Therefore

$$[C_k\,\rho\,V^3]\,/\,2d = \rho\,g\,S_0\,V \qquad (7.27)$$

with $\rho g S_0 V$: power made available per unit volume of water

From equation 7.27, the average velocity of the water element may then be expressed as

$$V = \sqrt{\frac{2gdS_0}{C_k}} \qquad (7.28)$$

From the above analyses it is evident that the principles of conservation of energy, momentum and power, yielded equations for mean velocity (equations 7.18, 7.23 and 7.28) which display the same form, i.e. the average velocity is directly related to the square roots of the cobble diameter (d), channel gradient (S_0) and a resistance coefficient (C_x):

$$V = \sqrt{2g}\sqrt{\frac{dS_0}{C_x}} \tag{7.29}$$

This equation differs from the conventional form of equation defining mean flow velocity in rivers (equation 7.1) and implies that under conditions of large scale roughness, the flow velocity is independent of flow depth. However, this may not be unrealistic considering that under conditions of large scale roughness energy losses are dominated by local effects related to individual bed elements, e.g. drag and wake effects, local accelerations and decelerations, local hydraulic jumps, etc.

7.4.2 Eddy theory

The second fundamental approach investigated the relationship between cobble diameter, the diameter of eddies that form next to the bed and the relative submergence under conditions of large scale roughness. Rooseboom (1974; 1998) has showed that under conditions of small scale roughness and uniform flow, the diameter of eddies next to the bed fit in with the size of the roughness elements. He subsequently derived an equation defining the mean velocity under turbulent boundary conditions in terms of the size of these boundary eddies. It was therefore hypothesized that, since turbulent flow prevails under conditions of large scale roughness in cobble bed rivers and shear stresses are generated by eddying motion on a large scale, the mean velocity under these conditions can also be expressed in terms of the size of the boundary eddies. Furthermore, if consistent relationships exist between the cobble diameter, the diameter of eddies which form next to the bed and the ratio of flow depth to cobble diameter, these relationships can be used to determine the mean velocity of flow under conditions of large scale roughness.

In order to investigate the above relationships, an understanding of eddy theory is required. The following paragraphs therefore provide a brief overview of eddy theory and define the relationships between mean velocity, flow depth and the size of boundary eddies.

Under conditions of steady uniform flow, from turbulent flow theory and the principle of momentum exchange across an eddy of radius R_d, it follows that (Rooseboom, 1974):

$$\tau(y) = \rho gs(D - y) = \frac{\rho}{2\pi} R_d^{\,2}\left(\frac{dv}{dy}\right)^2 \tag{7.30}$$

$$\Rightarrow \frac{dv}{dy} = \frac{\sqrt{2\pi gs(D-y)}}{R_d} \tag{7.31}$$

with $\frac{dv}{dy}$: angular velocity of the eddy (m/s)

$\tau(y)$: shear stress at distance y above the bed (N/m^2)

In turbulent flow, as layers of fluid cannot slip relative to each other due to the eddying motion, a thin vertical element therefore has to move as a unit (Rooseboom, 1974). As the velocity next to the boundary (at point 0) has to be equal to zero, the only way in which such an element can momentarily move as a unit, is by relative rotation around 0. However, such rotation is not possible, unless it is accompanied by translation of the centre of rotation. If V_0 equals the translatory velocity of the centre of rotation, it therefore follows that

$$V_0 = y\frac{dv}{dy} = \frac{y\sqrt{2\pi gs(D-y)}}{R_d} = \text{Constant} \tag{7.32}$$

since the centre of rotation is common to all elements in the vertical.

Close to the bed, R_d mathematically equals y and therefore, if $y = y_0$, the ordinate of the level at which the velocity is mathematically equal to 0, y can be equated to R_d. Therefore, equation 7.32 becomes

$$V_0 = \sqrt{2\pi gs(D-y_0)} \tag{7.33}$$

Furthermore, from the principle of conservation of power, it follows that

$$\int_{y_0}^{D} \rho gsv\,dy = \int_{y_0}^{D} \tau\frac{dv}{dy}dy \tag{7.34}$$

After integration, and by substituting equation 7.31 into equation 7.34, an equation for average velocity can be derived, viz.

$$V = \frac{V_0}{D-y_0}D\left(\ln\frac{D}{ey_0} + \frac{y_0}{D}\right) \tag{7.35}$$

Under conditions of small scale roughness, Rooseboom (1974) has proved that equation 7.35 simplifies to an equation with the form of equation 7.1, by showing that the ratio of y_0 to R_d is constant and by assuming that $D-y_0 \approx D$. However, under conditions of large scale roughness, due to the relative large boundary eddies in relation to flow depth and the nature of a heterogeneous cobble bed, the assumptions of a constant ratio between y_0 and R_d or that $D-y_0 \approx D$ are not obvious. Furthermore, under conditions of large scale roughness in a cobble and boulder bed river, the flow depth varies considerably within a cross section, which makes it difficult to define the location of the origin of the y-axis. To overcome this problem, average values of the parameters in equation 7.35 were defined. This was done by considering a cross section consisting of n_w vertical elements with height (y) and width (dW_T) as shown in Figure 7.2. The cross sectional flow area (A) therefore equals

$$A = \int y \, dW_T = dW_T \sum y = n_w dW_T \frac{\sum y}{n_w} = W_T \overline{D} \tag{7.36}$$

which means that $\overline{D}$ (the mean flow depth over the cross section) can be expressed as A/W_T.

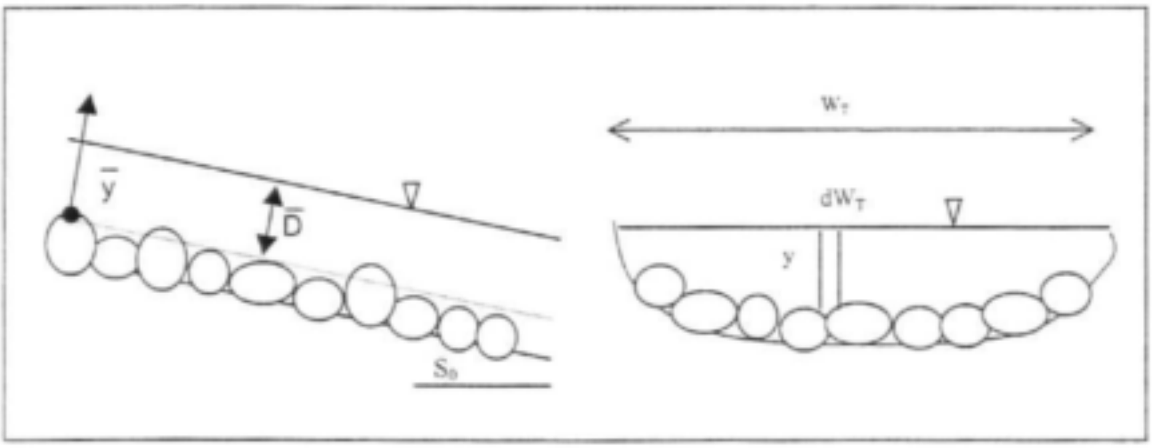


Figure 7.2 : Definition diagram

The parameter $\overline{D}$ may therefore be used to define a reference bed level in a heterogeneous cobble bed where the vertical axis (y axis) originates, as indicated in Figure 7.2. At low flows in a heterogeneous cobble bed river, y_0 in equation 7.35 can therefore be replaced by $\overline{y_0}$, representing the average ordinate level over the cross section at which the velocity is mathematically equal to zero. Equations 7.33 and 7.35 then become

$$\overline{V_0} = \sqrt{2\pi g s(\overline{D} - \overline{y_0})} \tag{7.37}$$

and

$$\overline{V} = \frac{\overline{V_0}}{\overline{D} - y_0}\overline{D}\left(\ln\frac{\overline{D}}{ey_0} + \frac{\overline{y_0}}{\overline{D}}\right) \qquad (7.38)$$

respectively. Equation 7.38 therefore represents an equation for the average velocity under conditions of large scale roughness and uniform flow.

7.4.3 Verification

In order to evaluate the applicability of the two theoretically based equations which were derived (equations 7.29 and 7.38), an extensive dataset was compiled from literature (Bathurst, 1978; Jarret, 1984; Bathurst, 1985), representing fifty measured values of mean velocity, bed particle size distribution, energy gradient, flow area and hydraulic radius over a range of discharges in cobble and boulder bed rivers, under conditions of large and intermediate scale roughness (refer to Appendix G). From this data, corresponding values of C_x (equation 7.29) and y_o (equation 7.38) were calculated, and their relationship with various physical parameters (e.g. absolute cobble size (d_{50}), relative submergence (R/d_{50}) and width to depth ratio (W/D)) subsequently investigated. It was found that, in the case of both C_x and y_o, the only significant correlation which emerged, is with the relative submergence (R/d_{50}).

From Figure 7.3 it is evident that good correlation exists between C_x and R/d_{50}. This is confirmed by the very high r^2 value (0.87) of a power form regression line (defined by equation 7.39) fitted to the data:

$$C_x = 0.5285\left(\frac{R}{d_{50}}\right)^{-2.166} \qquad (7.39)$$

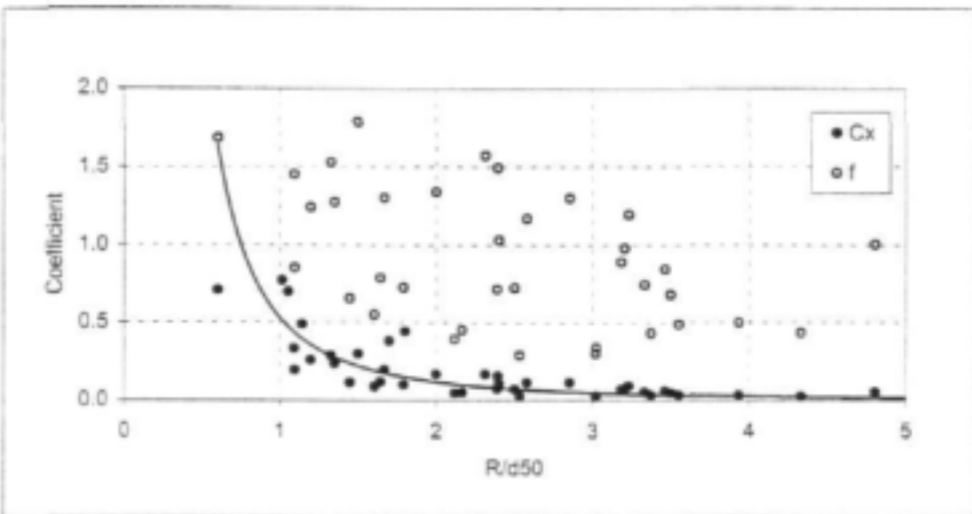


Figure 7.3: The relationship between C_x and R/d_{50}
(Darcy Weisbach f-values also indicated)

Also indicated on Figure 7.3 are corresponding values of the Darcy Weisbach resistance coefficient (f) as calculated from the Darcy Weisbach equation. It shows that, for the same data, the correlation between C_x and R/d_{50} is much higher than the correlation between f and R/d_{50}. The implication of this is that C_x provides a more consistent and accurate quantification of flow resistance under conditions of large scale roughness and does not seem to be as site specific as the Darcy Weisbach resistance coefficient.

In similar fashion to Figure 7.3, Figure 7.4 displays the relationship between the relative submergence and the ratio $\overline{y_0}/d_{50}$ and suggests that, as the ratio R/d_{50} decreases, there is a corresponding decrease in the value of $\overline{y_0}$. If it assumed that $\overline{y_0}$ is directly related to the size of the boundary eddies that fit in with the bed particles (which is true for conditions of small scale roughness), Figure 7.4 therefore implies that under conditions of large scale roughness, the development of boundary eddies is suppressed by the lower ratio of flow depth to particle size. However, a regression curve fitted to the data indicates a very poor correlation ($r^2 = 0.36$), which suggests that $\overline{y_0}$ (and therefore also the size of the boundary eddies) is probably not only a function of R/d_{50} but may also be related to other explanatory variables, e.g. particle shape, roughness concentration, standard deviation of particle size, etc., which would be difficult to define under field conditions.

The above therefore suggests that, whereas equation 7.29 can be used to estimate the mean velocity under conditions of large scale roughness, equation 7.38 is not suited for the calculation of mean velocity under these conditions.

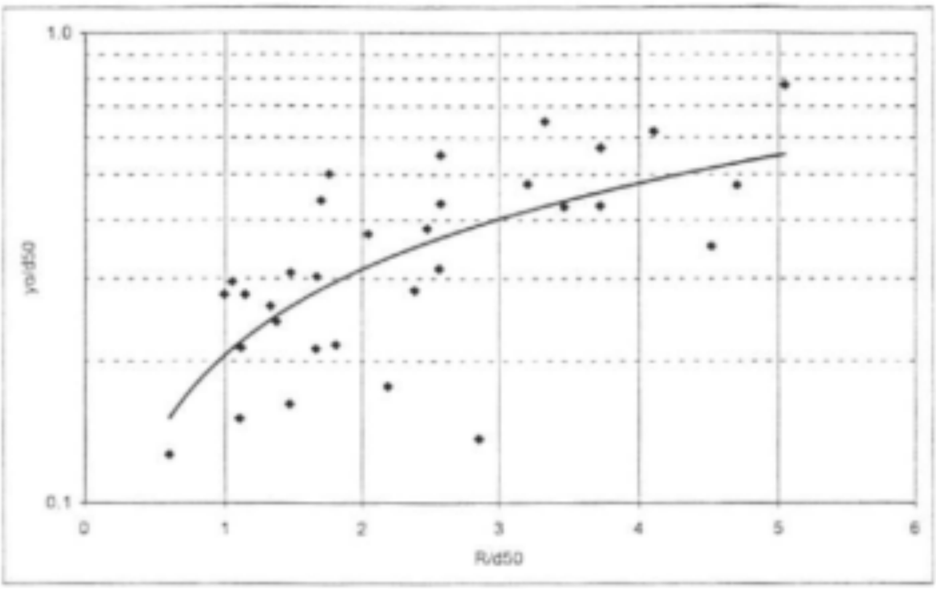


Figure 7.4: The relationship between the ratio $\overline{y_0}/d_{50}$ and relative submergence

7.5 The application of large scale roughness resistance equations to cobble and boulder bed rivers in the Western Cape

In this section the empirical and semi-empirical large scale roughness resistance equations listed in Table 7.2 (equations 7.5 to 7.13), as well as the fundamental, theoretically based equation (equation 7.29), were applied to cobble and boulder bed rivers in the Western Cape.

Three study reaches were selected, located in the Elands, Molenaars and Jonkershoek Rivers respectively. The reaches were between 50 and 70 m in length, straight and relatively uniform, with no disturbances due to vegetation or macro scale bed form irregularities. This allowed average flow conditions within the reaches to be considered uniform, even though locally the flow was non-uniform with zones of separation, acceleration and deceleration. Within each reach, the Wolman sampling method was used to determine the particle size distribution, while bed and water levels at 0.5 m intervals along three cross sections within each reach were surveyed with a dumpy level and staff. At different discharges, values of the wetted perimeter, flow area and hydraulic radius within each cross section were calculated and reach-averaged values of the hydraulic radius were then calculated based on the average of the three cross sections within the reach. At each discharge an average energy gradient (S_f) over the length of the reach was also determined, based on the difference in water surface elevation between upstream and downstream measurements. The actual discharge (Q_m) within each reach was determined from rating curves at nearby gauging weirs (Molenaars: H1H018; Elands: H1H033 and Jonkershoek: G2H037). Table 7.3 lists the relevant cross sectional data.

River	Cross Section No.	Qm (m3/s)	A (m2)	P (m)	R(m) (m)	Sf(%) %	R/d50
Jonkershoek d_{50}=0.144m	1	0.691	1.758	7.478	0.235	0.3	
	2		1.941	7.569	0.256		
	3		1.258	3.78	0.333		
	Average				**0.275**		**1.908**
	1	0.495	1.54	6.997	0.220	0.31	
	2		1.503	6.754	0.223		
	3		1.148	3.565	0.322		
	Average				**0.255**		**1.770**
	1	0.175	0.969	5.957	0.163	0.22	
	2		1.047	6.664	0.157		
	3		0.763	3.148	0.242		
	Average				**0.187**		**1.301**
	1	0.104	0.88	5.75	0.153	0.28	
	2		0.732	6.137	0.119		
	3		0.431	2.403	0.179		
	Average				**0.151**		**1.046**
Elands d_{50}=0.18m	1	0.19	1.292	8.48	0.152	0.4	
	2		1.327	9.314	0.142		
	3		1.494	11.715	0.128		
	Average				**0.141**		**0.782**
	1	1.115	4.037	12.26	0.329	0.21	
	2		3.767	13.005	0.290		
	3		4.24	16.96	0.250		
	Average				**0.290**		**1.609**
	1	0.365	2.759	10.258	0.269	0.28	
	2		2.303	10.465	0.220		
	3		2.435	15.842	0.154		
	Average				**0.214**		**1.190**
	1	0.19	1.331	7.9	0.168	0.5	
	2		1.466	9.869	0.149		
	3		1.371	12.65	0.108		
	Average				**0.142**		**0.788**
Molenaars d_{50}=0.16m	1	0.405	1.617	6.278	0.258	0.39	
	2		1.222	9.148	0.134		
	3		2.041	8.608	0.237		
	Average				**0.209**		**1.309**
	1	0.383	1.369	5.668	0.242	0.46	
	2		1.558	8.908	0.175		
	3		2.118	10.038	0.211		
	Average				**0.209**		**1.307**
	1	0.36	1.53	6.091	0.251	0.38	
	2		1.583	7.946	0.199		
	3		1.717	8.32	0.206		
	Average				**0.219**		**1.368**

Table 7.3: Cross section data and measured discharges

Within each reach, at each different discharge, values for the Darcy-Weisbach resistance coefficient (f) and the large scale roughness resistance coefficient (C_x) were calculated from equations 7.5 to 7.13 and 7.39 respectively. These values were then substituted into the Darcy Weisbach equation (equation 7.40) or equation 7.41 (derived from equation 7.29) to calculate corresponding discharge values, which were then compared to the measured discharge values.

$$Q = A\sqrt{\frac{8g}{f}}\sqrt{RS_f} \tag{7.40}$$

$$Q = A\sqrt{\frac{2gd_{50}S_0}{C_x}} \tag{7.41}$$

Table 7.4 displays the percentage error between the calculated and measured discharge values and indicates that only two equations consistently estimate the discharge fairly accurately, viz. equation 7.41 and equation 7.11 (Griffiths, 1981).

Study reach	Percentage error between calculated and measured discharge									
Eq. No.	7.41	7.5	7.7	7.7	7.8	7.9	7.10	7.11	7.12	7.13
JKH1	-39	-10	-1	-3	-44	-23	-45	-20	-42	103
JKH2	-33	2	12	10	-40	-13	-41	-12	-38	122
JKH3	-24	28	39	37	-45	8	-51	-6	-42	129
JKH5	-16	53	64	60	-54	28	-65	-5	-50	123
ELNDS1	-7	87	97	93	-79	57	-99	-15	-75	81
ELNDS2	-29	11	22	20	-39	-6	-42	-8	-37	130
ELNDS3	13	96	112	108	-25	65	-37	35	-21	225
ELANDS6	1	101	113	108	-77	69	-99	-7	-72	98
MOL1	-18	37	49	46	-40	13	-47	1	-44	128
MOL2	-3	63	77	73	-29	34	-37	19	-33	120
MOL3	-6	56	70	66	-28	29	-35	18	-32	169

Note: Shading indicates % error within 25 %

Table 7.4 : Percentage error between calculated and measured discharges for Western Cape data

The fact that only one of the nine empirical equations consistently provides a good estimate of the discharge, confirms the site specific nature of these equations and suggest that equation 7.11 was probably calibrated under conditions which are very similar to those in the study reaches. (A semi-logarithmic form equation (equation 7.42), which was calibrated with the data in Table 7.3 confirms this as it displays very similar coefficients to those of equation 7.11 (indicated in brackets)):

$$\sqrt{\frac{1}{f}} = 0.745(0.76) + 2.4(1.98)\log\frac{D}{d_{50}} \tag{7.42}$$

Furthermore, the fact that equation 7.41 provides fairly accurate estimates of discharge in most of the study reaches (for ten of the eleven cases within 30%), confirms that this equation can be considered more generally applicable than the site specific empirical and semi-empirical equations listed in Table 7.2. To illustrate this point, equations 7.41 and 7.11 were applied to an additional set of large scale roughness data from literature (Thorne and

Zevenbergen, 1985; refer to Appendix G) and resistance coefficients and corresponding discharge values were calculated. Figure 7.5 shows that whereas equation 7.41 again provides relatively accurate estimates of the actual discharge, equation 7.11 is much less accurate.

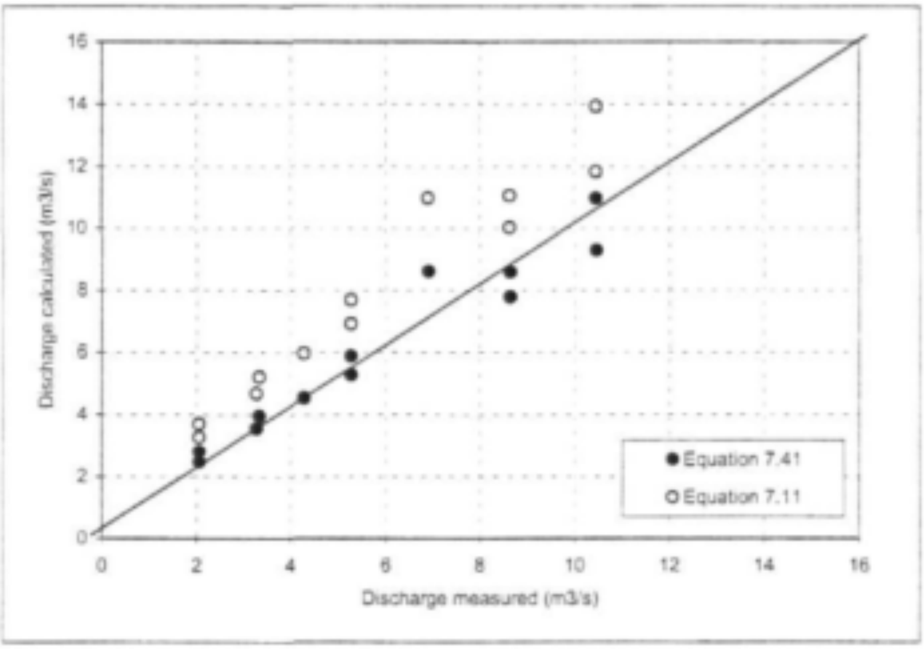


Figure 7.5: A comparison of calculated and measured discharge values for data from Thorne and Zevenbergen (1985)

7.6 Conclusion

A fundamental approach towards the estimation of mean velocity under conditions of large scale roughness led to the development of a relatively simple and generally applicable equation. With the aid of an extensive dataset from literature, the resistance coefficient in this equation (C_s) was calibrated and it was found that C_s displays a good correlation with relative submergence (R/d_{50}) and display less variability across different rivers and reaches than the Darcy Weisbach resistance coefficient (f), which is usually used to quantify flow resistance under conditions of large scale roughness. The application of this new equation to cobble and boulder bed rivers in the Western Cape, proved that it is able to provide a fairly accurate estimate of mean flow velocity under conditions of large scale roughness and can therefore be used for obtaining first order estimates of stage discharge relationships during the environmental flow assessment process.

The application of the Darcy Weisbach equation to cobble and boulder bed rivers in the Western Cape, with the resistance coefficient calculated from existing empirical and semi-empirical large scale roughness resistance equations, confirmed the site specific nature of these equations. Whereas some equations provided fairly accurate estimates of discharge, others led to significant over- or under estimations.

It is therefore recommended that the new, theoretically based equation (equation 7.29) be used as a generally applicable equation for obtaining a first order estimate of mean velocity under conditions of large scale roughness, with the corresponding flow resistance coefficient (C_x) estimated from equation 7.39. However, whenever more accurate estimates of mean velocity or discharge are required, it is recommended that the resistance coefficient (either C_x or f) be calibrated over a range of discharges under conditions similar to those for which they will be applied.

8. HYDRAULIC CHARACTERISTICS AND THE INSTREAM HABITAT

8.1 Introduction

A variety of factors control the abundance, distribution and productivity of aquatic organisms in rivers. These include competition for space, predation, chemical water quality, nutrient supplies, flow patterns, and flow variability and together describe the biological, chemical and physical habitat (Gordon *et al.*, 1992). Chemical water quality has traditionally been viewed as the most important factor affecting the degradation of lotic systems (Hugues *et al.*, 1990). However, the physical habitat and its modifications have recently been identified as a key element in stream ecosystem functioning (Lamouroux *et al.*, 1995). The physical habitat refers to those factors, which form the "structure" within which an organism makes its home. Physical factors are generally more predictable, less variable and more easily measured than biological or chemical ones, and are thus preferable for general, consistent descriptions of streams (Richards, 1976). The physical factors which are ecologically most significant include temperature, channel morphology (channel shape, morphological structure and substrate characteristics) and local hydraulic conditions (flow velocity, flow depth, lift and drag forces, shear velocity, wake zones behind objects, etc.).

Since the morphological characteristics of cobble and boulder bed rivers have already been addressed in Part II of this report, the current chapter focuses on the physical habitat in these rivers as determined by local hydraulic conditions.

8.2 The physical habitat as determined by local hydraulic conditions

8.2.1 The hydraulic environment

The interaction between channel morphology and streamflow determines the hydraulic conditions within a river channel, which in turn control ecosystem functioning through the availability of physical (hydraulic) habitat. During the environmental flow assessment process, hydrological data, in the form of a simulated, daily discharge regime, therefore needs to be translated into point discharge values and further into local hydraulic conditions in order to assess the ecological impact of an altered discharge regime.

The local hydraulic conditions in a river channel may be considered at two scales, viz. the macro- and micro environments (Davis and Barmuta, 1989). The macro environment reflects the mean flow component within a vertical water column as described by the mean velocity and flow depth. Water depth affects water temperature, light penetration and hydrostatic pressure, while stream velocity determines the rate at which nutrients and oxygen are supplied and waste products are removed. Various quantitative models for predicting habitat quality in terms of flow velocity and flow depth, have been developed. PHABSIM II for example, which is incorporated in the Instream Flow Incremental Methodology (Bovee, 1982), simulates velocity and depth characteristics by compartmentalizing cross sections into grids of lateral cells extending halfway to adjacent cross sections and assuming that the hydraulic conditions within these cells remain constant. The available habitat is then based on species preference for depth and average velocity.

Near the river bed, the velocities are much lower than in the water column above because of frictional resistance, while the shear stresses are relatively high. In this near bed region, known as the micro environment, the focus is on patterns of viscous action as fluid passes over a solid surface. Finer scale turbulence, such as the small eddies behind objects and velocity fluctuations near the surfaces of solids, become important. Hydraulic concepts which are of ecological importance in this environment include the thickness of the laminar sublayer, the shear velocity, the surface roughness, lift and drag forces and wake zones behind objects (Gordon *et al.*, 1992).

8.2.2 Describing the hydraulic habitat

i. Cross sections

Traditionally, ecologists have used surveyed cross sections to describe the local hydraulic conditions within a river. Typically, cross sections describe the flow width, flow depth, flow area and wetted perimeter. Usually, the velocity-area method is used to calculate the mean velocity and discharge and this provides some indication of velocity variation across the section. Although it is a cost-effective and relatively informative approach, description of the physical habitat in terms of cross sections does have shortcomings. Firstly, intuitive understanding of the data and the river is obscured. Although it provides simple and precise output, it is not necessarily sympathetic to the ecologist's "feel" for the river ecosystem (King and Schael, 2001). Furthermore, the scale at which cross-sectional surveys are done, leads to an under-representation of the true hydraulic conditions within the river. This is of concern, because there has been increasing recognition of the importance of habitat patchiness, or physical heterogeneity in freshwater ecosystems and dissatisfaction with the inability to adequately describe this with cross-sectional data (King and Schael, 2001).

ii. Habitat mapping

A new field of science known as : hydraulic stream ecology, ecohydraulics, habitat hydraulics (Newson *et al.*, 1998), or similar, has evolved to study the links between physical (mainly hydraulic) conditions in rivers and biotic distributions, as well as to develop predictive capacity of how riverine biotas respond to changes in these physical conditions (King and Schael, 2001). Along with this development, habitat mapping has developed as a method for linking ecological and physical conditions, describing the physical and hydraulic conditions within reaches at a relevant biological scale. Unlike cross sections, habitat mapping describes the mosaic of physical habitat conditions within the reach under consideration. It is primarily concerned with two variables, viz. the flow type, which is linked to the appearance of the water surface, and the substrate, which not only determines channel roughness, but also determines the suitability of the river bed for colonization by aquatic fauna and flora.

Figure 8.1 : A typical "habitat map" in the Lang river, Jonkershoek. The colours indicate different flow types and substrate classes (with acknowledgement to J.M. King)

8.3 Low flow hydraulic characteristics

8.3.1 Background

As mentioned before, average hydraulic parameters do not represent the diversity of hydraulic conditions within reaches. Subsequently, in order to describe hydraulic habitat diversity, much more emphasis is being placed on the spatial variability or heterogeneity of hydraulic conditions within a reach, with recent studies emphasizing the importance of the variability of local sets of point velocities, flow depths, roughness, or combinations thereof on hydrodynamic habitats (Lamouroux *et al.*, 1995; Waters, 1976; Bovee and Cochnauer, 1977; Orth and Maughan, 1982). This is of particular importance in cobble and boulder bed rivers, where the effect of large-scale roughness is dominant, complex flow patterns occur and the average, cross-sectional hydraulic parameters as such do not represent the diversity of hydraulic conditions occurring within the reach, especially during low flows.

This part of the research therefore addresses the spatial variation of hydraulic conditions in cobble and boulder bed rivers of the Western Cape. Only the macro hydraulic environment, as defined by the average flow velocity and flow depth within a water column, was considered, as these hydraulic parameters are adequate for the identification of general hydraulic patterns. The dominant morphological units as identified in these rivers (i.e. pool, plane bed, riffle and rapid morphological units), serve as the basic elements in providing the spatial framework for the hydraulic classification of zones or areas within which similar hydraulic patterns occur. The analyses are based on data collected during the months of November to May, representing the period of summer low flows in Western Cape rivers. The motivation for this is as follows: Firstly, summer low flows represent a critical period for the aquatic habitat and the hydraulic conditions during this period are of great ecological significance. Secondly, especially in cobble and boulder bed rivers, low flow hydraulics are extremely diverse and complex and very difficult to describe with conventional methods. Thirdly, by collecting all the data during the same stage of the annual flow regime viz. summer low flows, a consistent database was created, making comparison between the various study reaches possible. Finally, the low flows facilitated data collection in terms of accessibility and subsequently improved accuracy.

8.3.2 Data collection

Hydraulic data were collected within nine of the thirteen study reaches in which morphological data was previously collected (refer to Table 5.1). Due to time constraints, data could not be collected in all thirteen reaches. However, the nine reaches are representative of all the catchments and reach types under consideration and provided an extensive dataset for further analyses. Within each study reach, cross sections were surveyed and velocity and depth measurements were taken. A maximum of six cross sections were surveyed per reach, with at least one cross section per morphological unit. The surveys, which were performed with a theodolite and survey staff, provided information on channel form, flow area, flow width, the wetted perimeter and the hydraulic depth. (The cross sections are attached as Appendix H). Velocity and depth measurements were taken at regular intervals across each cross section (0.5 m or 1.0 m depending on channel width), as well as randomly, on a grid basis within each morphological unit represented by a cross section. Between 20 and 60 measurements were made per morphological unit. Point velocities were measured with an electromagnetic flow meter at 0.4 times the flow depth from the channel bottom. It is realized that due to large-scale roughness and its effects on the logarithmic velocity profile, these measurements do not necessarily reflect the average flow velocity. However, by taking all velocity measurements at the same relative level, consistency was ensured. (Although the majority of flow velocities represent flow in the downstream direction, which was the dominant flow direction, it does occasionally represent flow in other directions, e.g. transverse or reverse flow.) The flow depth at each point was measured with a wading rod. Based on the measurements within each cross section, the velocity area method was used to calculate discharge. (Point velocity and flow depth data are attached as Appx. I).

In order to determine the hydraulic characteristics of the study reaches, velocity and depth data from similar types of morphological units were combined and box and whisker plots were then used to represent their distribution in terms of the median, 25th and 75th percentile values, and extreme (maximum and minimum) values (Figures 8.2, 8.4, 8.6 and 8.7).

8.3.3 Velocity characteristics

Figure 8.2 shows the distribution of point velocities and indicates that the magnitude and range of flow velocities progressively increase from pool morphological units to plane beds to riffles and rapids. It shows the homogeneity associated with velocities in pool morphological units and the significant variability of velocities in riffles and rapids, which are characterized by much steeper gradients and more turbulence.

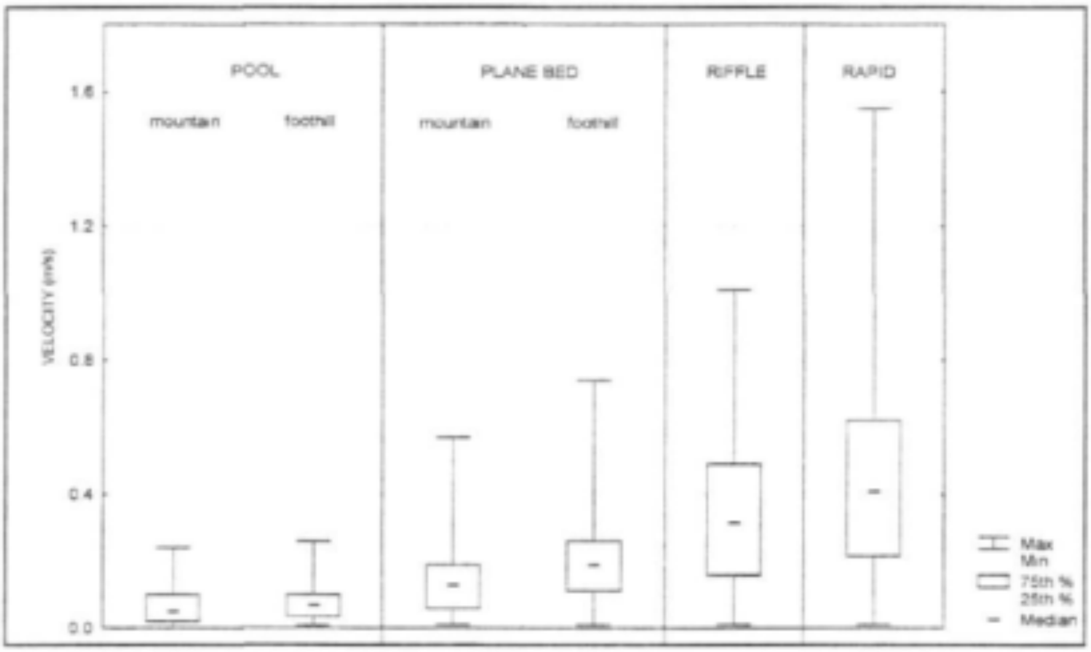


Figure 8.2 : Velocity characteristics

Furthermore, in the case of pool morphological units, the diagram shows that pools within the mountain and foothill zones, exhibit similar flow velocity characteristics. However, within plane bed morphological units, the diagram suggests that those within the foothill zones (characterized by larger relative flow depths) have slightly larger velocities than those in the mountain zones (which exhibit higher channel roughness). In the case of riffle and rapid morphological units, the rapids, which are characterized by larger bed particles and lower relative flow depths, display more variation than riffle morphological units, as indicated by the higher maximum and 75th percentile values.

As part of determining the velocity characteristics of cobble and boulder bed rivers, velocity profiles were measured within the various types of morphological units as shown in Figure 8.3. The diagram indicates that different types of morphological units are associated with different velocity profile characteristics. In the case of pool morphological units, for example, there is not much change in velocity within the vertical water column, whereas riffles and rapids display an almost linear increase of velocity with flow depth. Only on plane beds, does the velocity profile seem to approximate a logarithmic velocity profile. This can be expected, as the flow conditions on plane beds are very similar to uniform flow dominated by boundary resistance. Flow in pools is dominated by the backwater effect behind hydraulic controls, while riffles and rapids are characterized by extreme turbulence and large scale roughness.

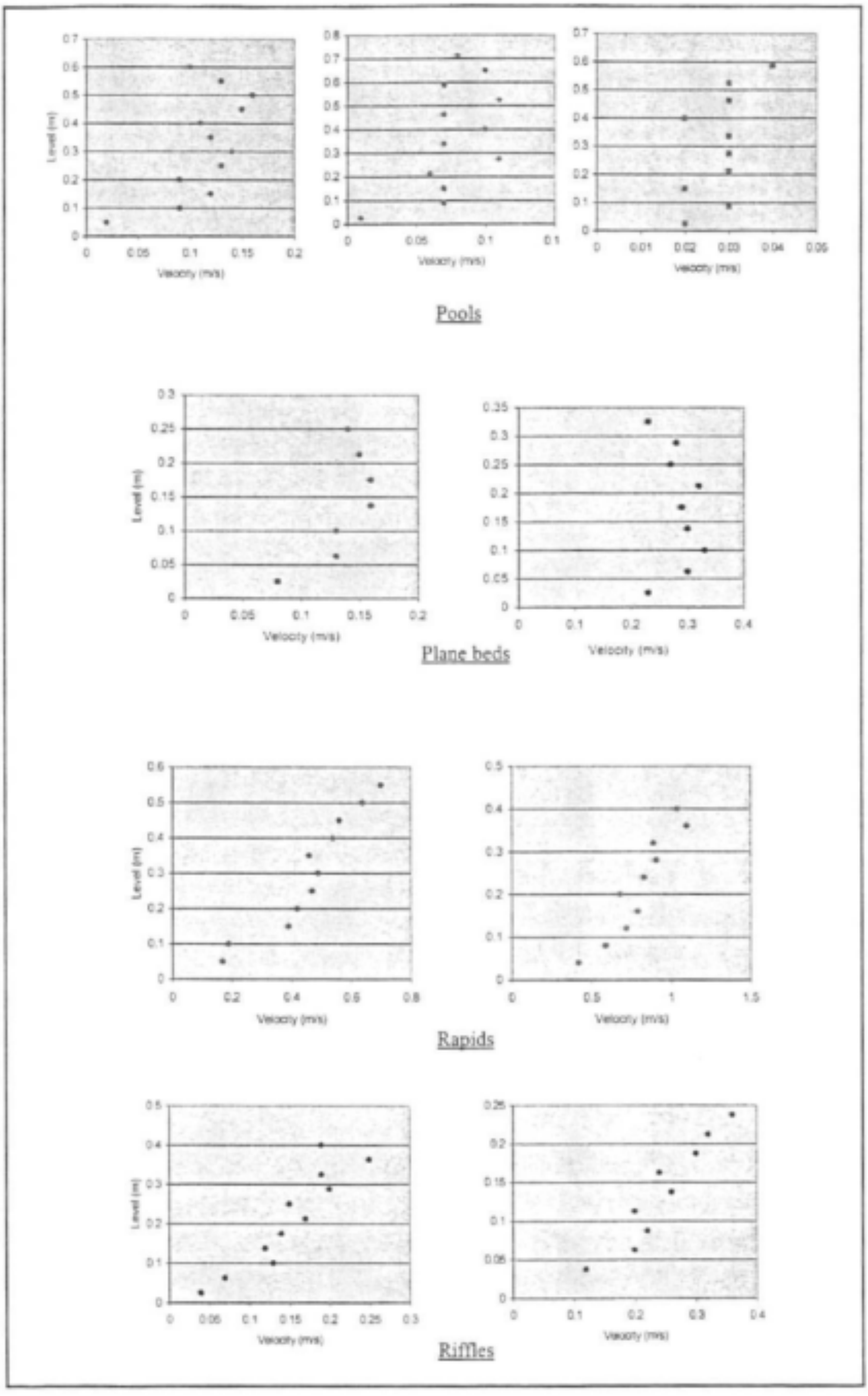


Figure 8.3 : Velocity profile characteristics

8.3.4 Flow depth characteristics

Flow depth characteristics within cobble and boulder bed rivers during summer low flows are indicated in Figure 8.4. It shows that the smallest flow depths are associated with riffle and rapid morphological units, while plane bed and pool morphological units are characterized by progressively larger flow depths.

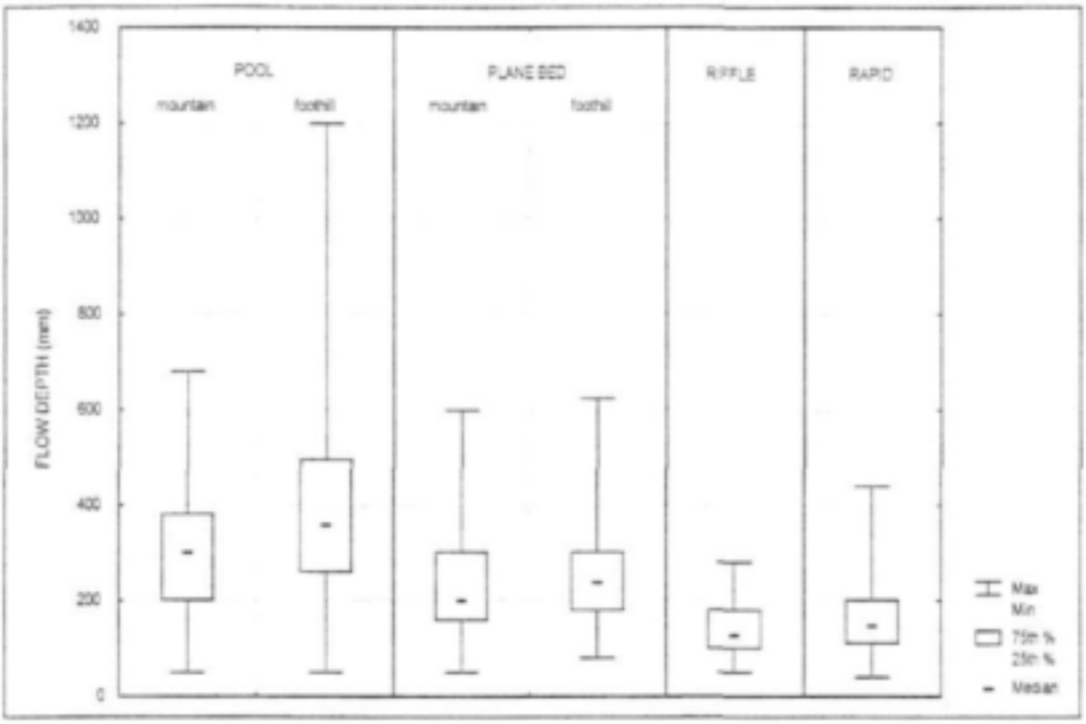


Figure 8.4 : Flow depth characteristics

In pool morphological units, the flow depth seems to be affected by the location within the longitudinal profile, with pools in the foothill zones generally a bit deeper than pools in the mountain zone. This might be attributed to the lower reach gradients in the foothill zones as well as to the increase in discharge as one progresses down the river. In plane bed morphological units, flow depth displays no correlation with the longitudinal zonation. In rapid and riffle morphological units, although the median and quartile values are almost similar, the maximum flow depth in rapid morphological units is larger than in riffles.

Figure 8.5 displays the variation of relative submergence (the ratio of average flow depth (D) to the median particle diameter (d_{50})) with channel gradient, as measured within the study reaches. It shows a similar trend for pools, plane beds, riffles and rapids, with the relative submergence decreasing as the average channel gradient increases. While the relative depth in pools is generally larger than 1, the relative depth within rapids and riffles, is less than 1, except at very small channel gradients.

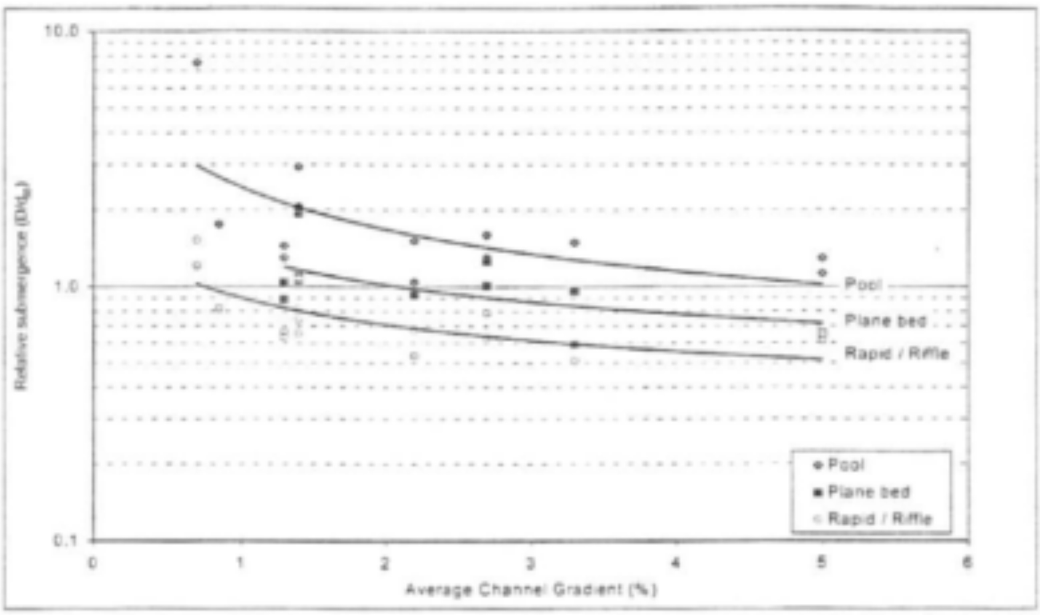


Figure 8.5 : The variation of relative submergence with average channel gradient

8.3.5 Froude number characteristics

Since the Froude number (refer to equation 3.2) is a dimensionless indication of the state of flow (sub- or supercritical; downstream- or upstream controlled etc.) and is a function of both flow velocity and flow depth, it is ideally suited to represent the hydraulic conditions within the various types of morphological units. Figure 8.6, which displays the variability in Froude numbers within each type of morphological unit during the summer low flow period, indicates that similar Froude number characteristics are associated with similar types of morphological units. It is found that :

- The magnitude and variability of Froude numbers increase progressively from pools to plane beds to riffles and rapids.
- Pool morphological units have Froude numbers less than 0.2, with 75 % of the values less than 0.1.
- Plane beds have Froude numbers within the range of 0.0 to 0.6.
- Pools within the foothill and mountain zones have fairly similar Froude number characteristics, as do plane beds.
- Rapids and riffles have relatively high Froude numbers as well as a high degree of variability.

- Riffles display less variability in Froude number values than rapids, which are characterized by higher local gradients and more turbulence.
- Overall, flow within riffle and rapid morphological units is subcritical, with only the extreme values within the supercritical range. This can be ascribed to the high relative roughness during low flow conditions, which leads to local areas of supercritical flow being limited to those areas where the flow is funnelled inbetween two boulders or cobbles, or where flow takes place over a cobble or boulder with a subsequent hydraulic jump immediately downstream.

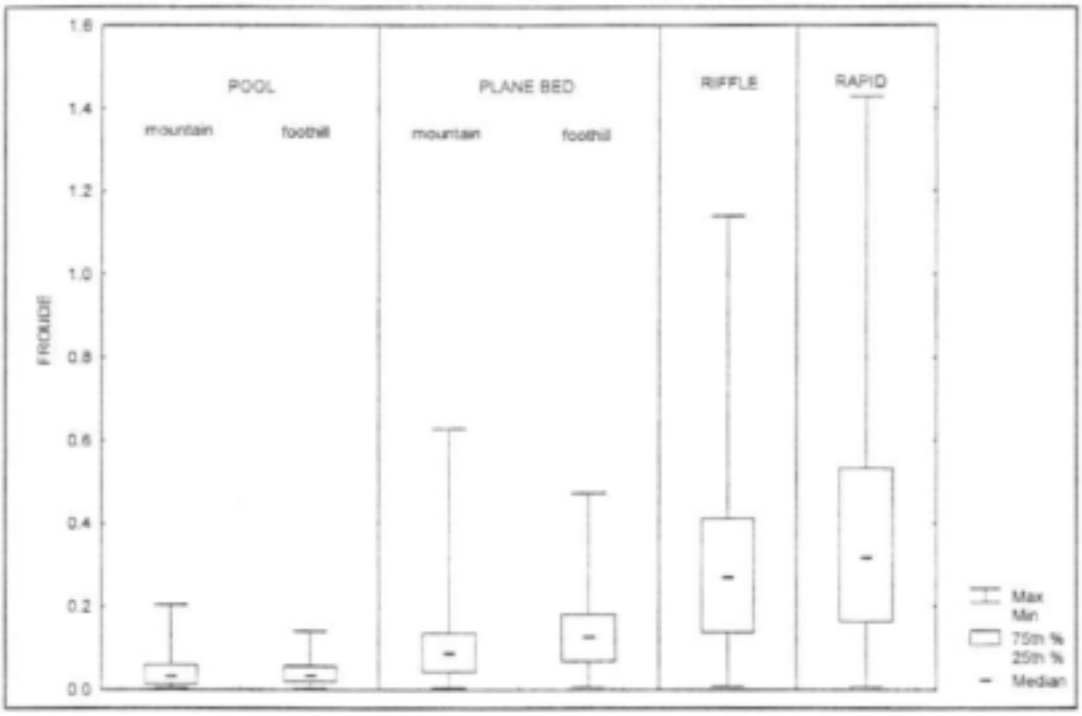


Figure 8.6 : Froude number characteristics

8.3.6 The velocity / depth ratio

Generally, the distribution of the velocity/depth ratio (Figure 8.7) follows a very similar pattern to Froude numbers. It shows that in the case of both pool and plane bed morphological units the mountain zones are characterized by larger extreme values than the foothill zones, which might be attributed to higher gradients, lower flow depths and higher velocities within the mountain zone. As in the case of flow velocity as well as the Froude number, the V/D ratio in rapids is larger and displays more variability than in riffles.

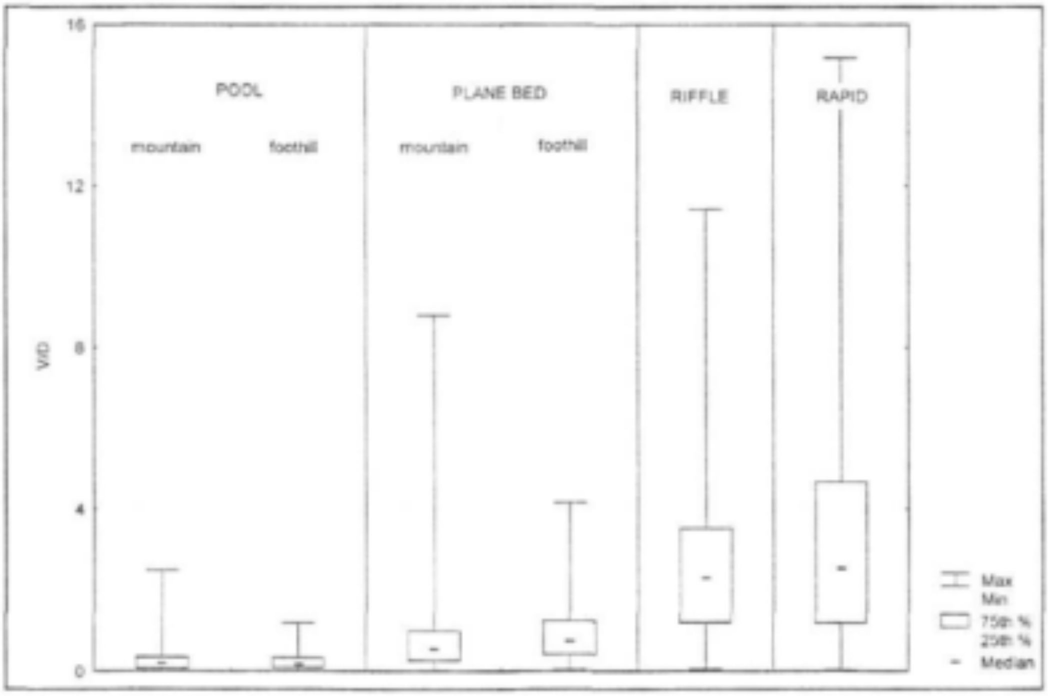


Figure 8.7 : Velocity-depth ratio characteristics

8.4 Instream habitat characteristics

8.4.1 Introduction

The instream habitat refers to the discharge dependent, ecologically significant instream flow environment and is distinguished from the more stable channel form features recognized in fluvial geomorphology (Wadeson and Rowntree, 1999). Furthermore, the scale at which the instream habitat is described (± 1 m^2) is much smaller than the channel wide scale used for the description of morphological units.

Biologists use habitat types to partition sample variance along a river, often limiting samples to one habitat type or basing stratified sampling procedures on the habitat types, assuming that physical conditions within the habitat types and the differences between them will be reasonably consistent (Jowett, 1993). The objective and consistent identification of the different habitat types is therefore very important and various studies have been directed towards the characterization of habitat types in terms of their hydraulic characteristics (Jowett, 1993; Wadeson, 1996; Wadeson and Rowntree, 1999).

This part of the research addresses the instream habitat characteristics in cobble and boulder bed rivers of the Western Cape in terms of the flow type (describing the appearance of the water surface) and the substrate class. During the collection of hydraulic data within the various study reaches, the flow type and the substrate class at each measurement point were noted – attached as Appendix I. Flow types were classified based on the categories as shown in Table 8.1, while substrate classes were identified in accordance with Table 4.1. Furthermore, in line with the recognition of instream habitats as having distinct hydraulic and substrate characteristics, the morphologically based hydraulic biotope concept as defined by Wadeson (1996) was also used to distinguish between different habitat types (Table 8.2). This was achieved by assigning each data point to a specific biotope class based on the combination of flow type and substrate as defined in the so-called hydraulic biotope matrix (Table 8.3) (Rowntree, 1996). (By using this matrix for the classification of hydraulic biotopes, consistency was ensured. However, cognisance should be taken of the fact that some measurement points which are characterized by flow types not included in the matrix, could not be assigned to any specific biotope class.)

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 (B)	Water forming bubbles, as in rapidly boiling water; usually below waterfall / 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 (ST)	Water flowing rapidly in a smooth sheet of water; similar to a chute but not forced between two bed elements
Broken standing wave (BSW)	Standing waves present which break at the crest (white water)
Undular standing wave (USW)	Standing waves form at the surface. No broken water
Fast riffle flow (FRF)	Very shallow, fast flickering flow, still covering most of the substrata
Rippled surface (RS)	Water surface has regular 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)	Water surface remains smooth. Streaming flow takes place throughout 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 suspended matter
No flow (NF)	No water movement

Table 8.1: Categories of visually distinct flow types (King and Schael, 2001)

Hydraulic biotope	Definition
Backwater	A backwater is morphologically defined as an area alongside but physically separated from the channel, but connected to it at its downstream end. Water therefore enters the feature in an upstream direction. It may occur over any substrate.
Slackwater	Slack water is an area of no perceptible flow which is hydraulically detached from the main flow, but is within the main channel. It may occur at channel margins or in midchannel areas downstream of obstructions or secondary flow cells. It may occur over any substrate.
Pool	A pool is in direct hydraulic contact with upstream and downstream water but has barely perceptible flow.
Glide	A glide exhibits smooth boundary turbulence, with clearly perceptible flow without any surface disturbance. A glide may occur over any substrate as long as the depth is sufficient to minimise relative roughness. Thus glides could only occur over cobbles at relatively high flows. Flow over a glide is uniform such that there is no significant convergence or divergence.
Chute	Chutes exhibit smooth boundary turbulence at higher flow velocities than glides. They typically occur in boulder or bedrock channels where flow is being funneled between macro bed elements. Chutes are generally short and exhibit flow acceleration.
Run	A run is characterized by a rippled flow type and can occur over any substrate apart from silt. Runs often form the transition between riffles and the downstream pool. It may be useful to distinguish between fast and slow runs in terms of the degree of ripple development. A fast run has clear rippling, a slow run has indistinct ripples.
Riffle	Riffles may have undular standing waves (no broken water) or breaking standing waves (white water) and occur over coarse alluvial substrates from gravel to cobble.
Rapid	Rapids have undular standing waves or breaking standing waves and occur over a fixed substrate such as boulder or bedrock.
Cascade	A cascade has free-falling flow over a substrate of boulder or bedrock, but the flow maintains contact with the substrate. Small cascades may occur in cobble where the bed has a stepped structure due to cobble accumulations.
Waterfall	A waterfall has free falling flow over a cliff, where a cliff represents a significant topographic discontinuity in the channel long profile.
Boil	A boil may occur over any substrate and consists primarily of vertical flow.

Table 8.2 : Hydraulic biotope definitions (Wadeson, 1996)

Substrate	Hydraulic biotope class							
Silt	Backwater	Pool	Glide					Boil
Sand	Backwater	Pool	Glide	Run			Mixed	Boil
Gravel	Backwater	Pool	Glide	Run	Riffle		Mixed	Boil
Cobble	Backwater	Pool	Glide	Run	Riffle	Cascade	Mixed	Boil
Boulder	Backwater	Pool	Chute	Run	Rapid	Cascade	Mixed	Boil
Bedrock (Fractured)	Backwater	Pool	Chute	Run	Rapid	Cascade	Mixed	Boil
Bedrock (Smooth)	Backwater	Pool	Glide	Run	Rapid	Cascade	Mixed	Boil
Cliff						Waterfall		
Flow type	No flow	Barely perceptible flow	Smooth and turbulent	Ripples	Undular/ Breaking standing waves	Free falling	Chaotic flow	Vertical flow

Table 8.3 : The hydraulic biotope matrix (Rowntree, 1996)

8.4.2 Habitat diversity

Habitat diversity was described in terms of both flow types and biotope classes. Not only does this provide insight into the relationship between morphologically based biotopes and flow types, but it also allows a clear picture of the "visual" interpretation of the reach . Data from similar types of morphological units within the different study reaches were combined and two sets of pie charts, showing the percentage distribution of flow types and hydraulic biotope classes respectively, were then used to assess habitat diversity within the different morphological unit types. The pie charts give a useful visual indication of both flow type and biotope diversity as well as the dominant flow types or biotope classes within each type of morphological unit.

i. Pools

Figure 8.8, which shows the diversity of flow types and biotope classes in pool morphological units, indicates that in pool morphological units during summer low flows, the dominant biotopes are pools and glides, while barely perceptible flow and smooth boundary turbulent flow types dominate. Furthermore, it shows that whereas run biotopes and the rippled surface flow type are present in pools in the mountain zones, pools within the foothill zones contain almost none. This might be due to the slightly deeper pools within the foothill zones as described in paragraph 8.3.4. Finally, it can be seen that the reach at Vlottenburg, a reach in the lower foothill zone, which is characterized by meandering and very deep pools, display very little habitat diversity.

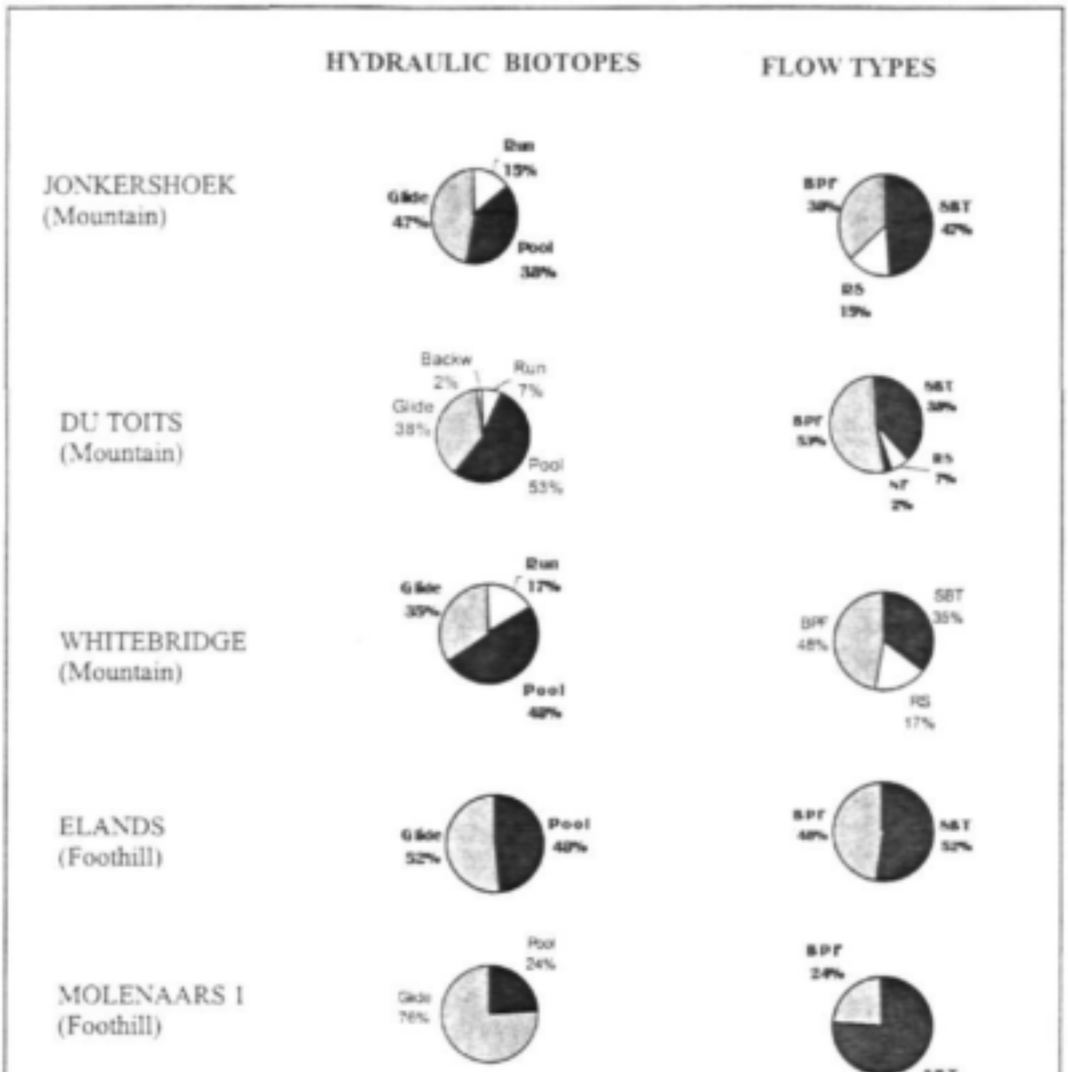


Figure 8.8 : Habitat diversity in pool morphological units

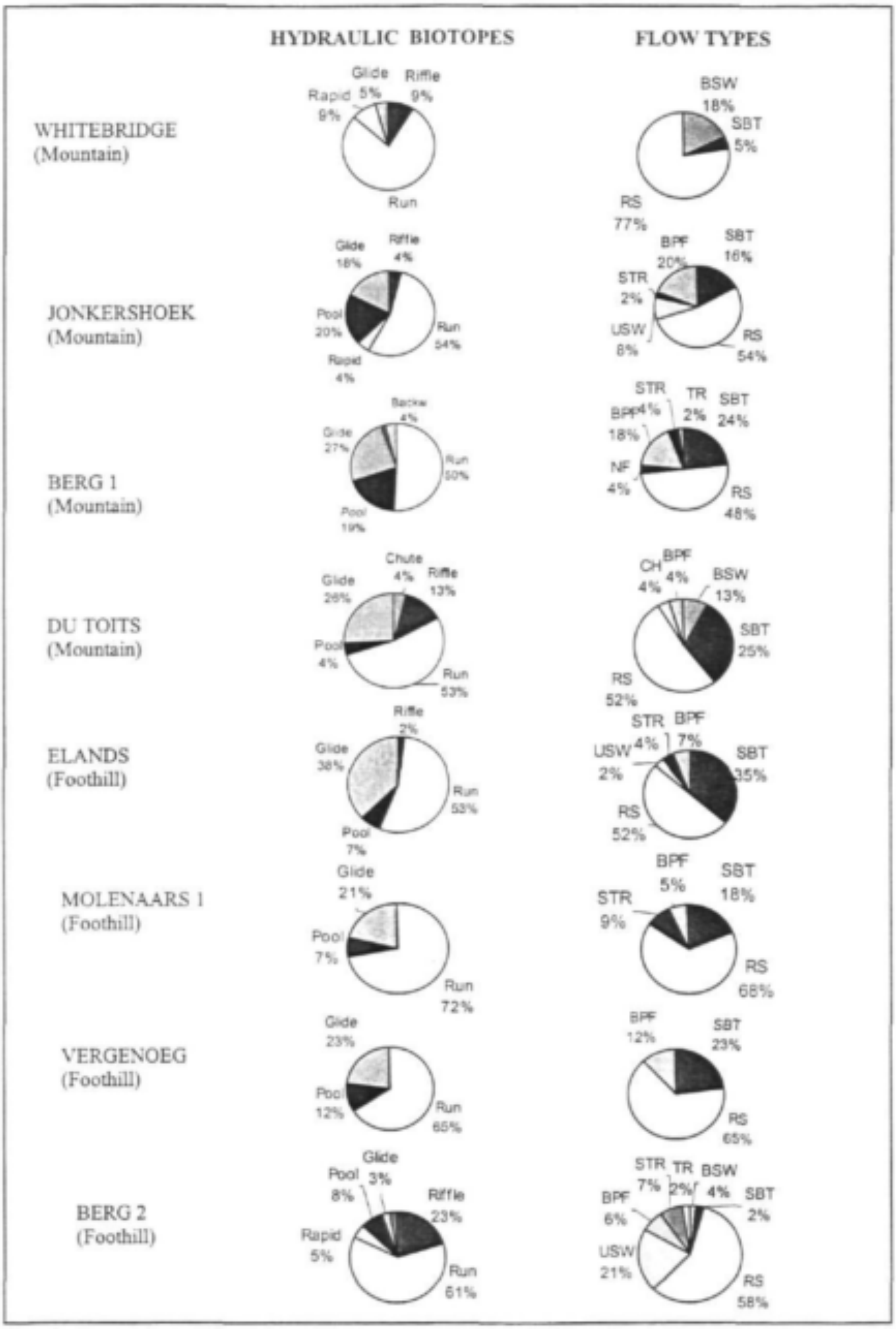


Figure 8.9 : Habitat diversity in plane bed morphological units

ii. Plane beds

From Figure 8.9 it can be seen that plane bed morphological units are characterized by a high percentage of run biotopes. They display more habitat diversity than pool morphological units, with pool, glide, riffle, rapid and even chute biotopes being present, although in low percentages. The dominant flow types are the rippled surface and smooth boundary turbulent types, although the broken and undular standing wave, stream as well as barely perceptible flow type are also present.

iii. Riffles and Rapids

Figures 8.10 and 8.11, which show the habitat diversity in riffle and rapid morphological units, clearly indicate the extreme habitat diversity associated with these morphological units in comparison to pool and plane bed morphological units. In rapid morphological units, either the riffle or rapid biotope dominates, while in riffle morphological units, the riffle biotope is dominant. A wide variety of flow types occur in these morphological units. The dominant flow types, however, are broken standing waves, undular standing waves and rippled surface.

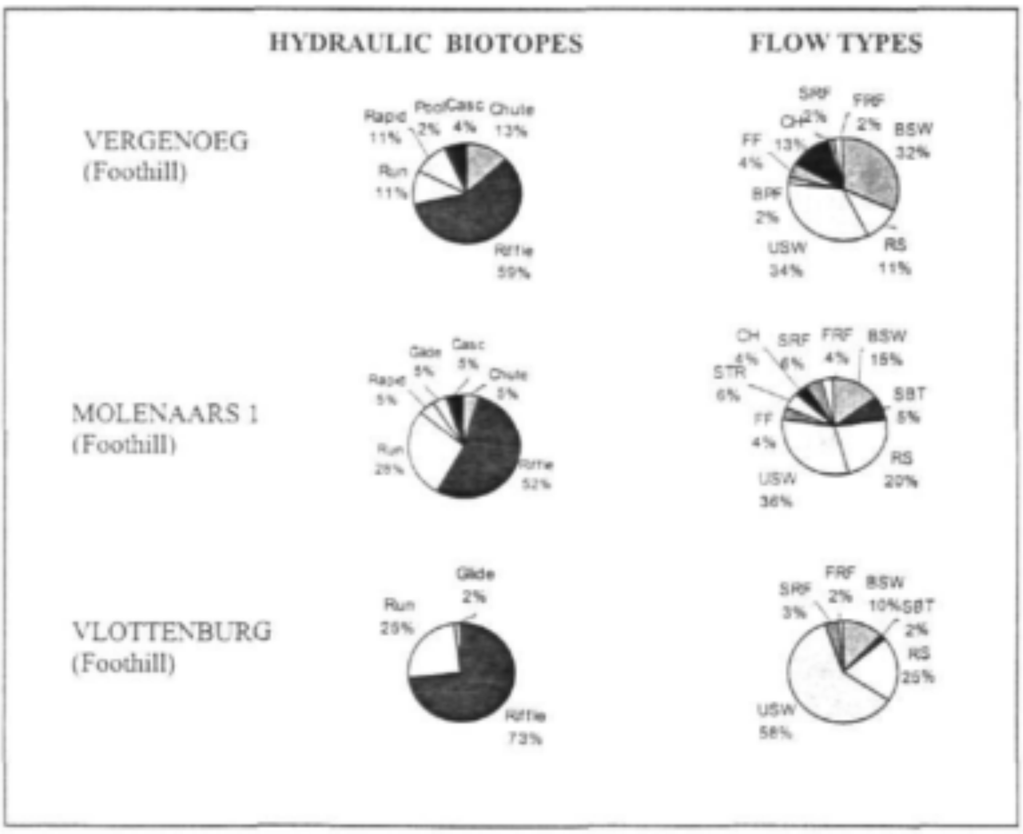


Figure 8.10 : Habitat diversity in riffle morphological units

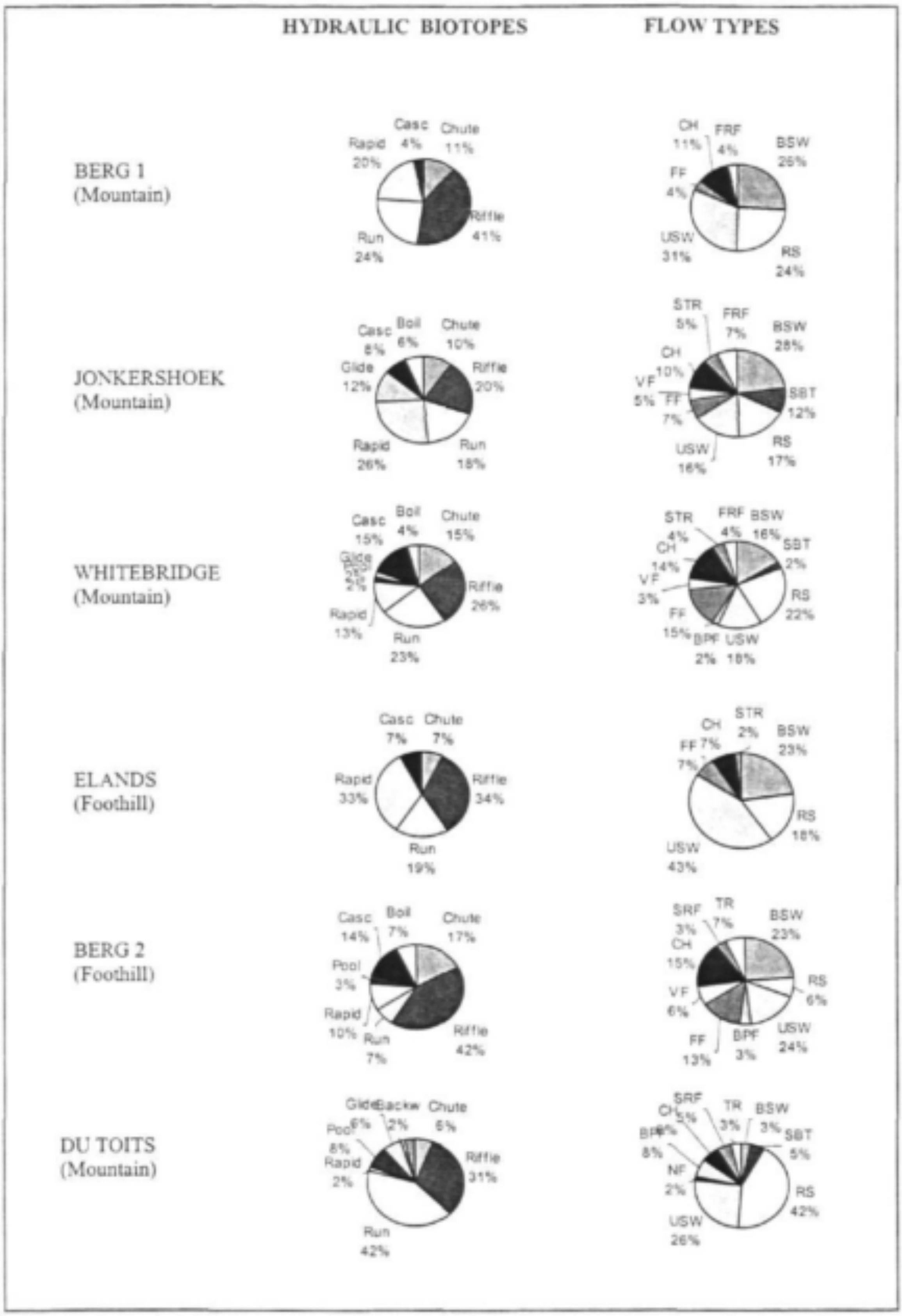


Figure 8.11 : Habitat diversity in rapid morphological units

8.4.3 The hydraulic classification of instream habitats

The objective identification of different habitat types is very important and various studies have been directed towards the characterization of habitat types in terms of their hydraulic characteristics (Jowett, 1993; Wadeson, 1996; Wadeson and Rowntree, 1998). Wadeson and Rowntree (1998) for example, used hydraulic indices (Froude number, Reynolds number, the velocity/depth ratio, the roughness Reynolds number and the shear velocity) to describe the hydraulic characteristics of different biotope classes and found that hydraulic biotope classes can be considered as significantly different in terms of flow hydraulics. In paragraph 8.3 it was shown that the different types of morphological units are characterized by different hydraulic characteristics in terms of flow velocity, flow depth, Froude number and the velocity-depth ratio. Similarly, in paragraph 8.4.2 it was shown that there exists a definite correspondence between habitat diversity and morphological unit type. This suggests that within the cobble and boulder bed rivers of the Western Cape, different hydraulic conditions, as described by the flow velocity, flow depth, Froude number and velocity/depth ratio, are representative of different habitat types. Consequently, data points representative of similar biotope classes and flow types within pool, plane bed and riffle and rapid morphological units respectively, were combined and their relationship with their hydraulic characteristics investigated. Figures 8.12 a and b, for example, which shows the velocity characteristics of different biotope classes and flow types (as defined by the mean, the standard deviation (SD) and the standard error of the mean (SE)), confirms that different biotope classes and flow types are characterized by different velocity characteristics.

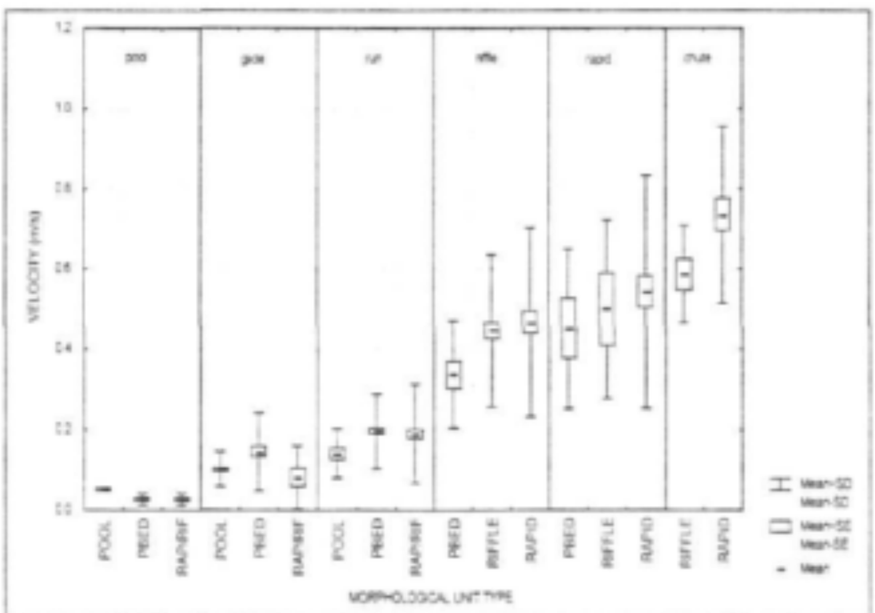


Figure 8.12a : Velocity characteristics of biotope classes

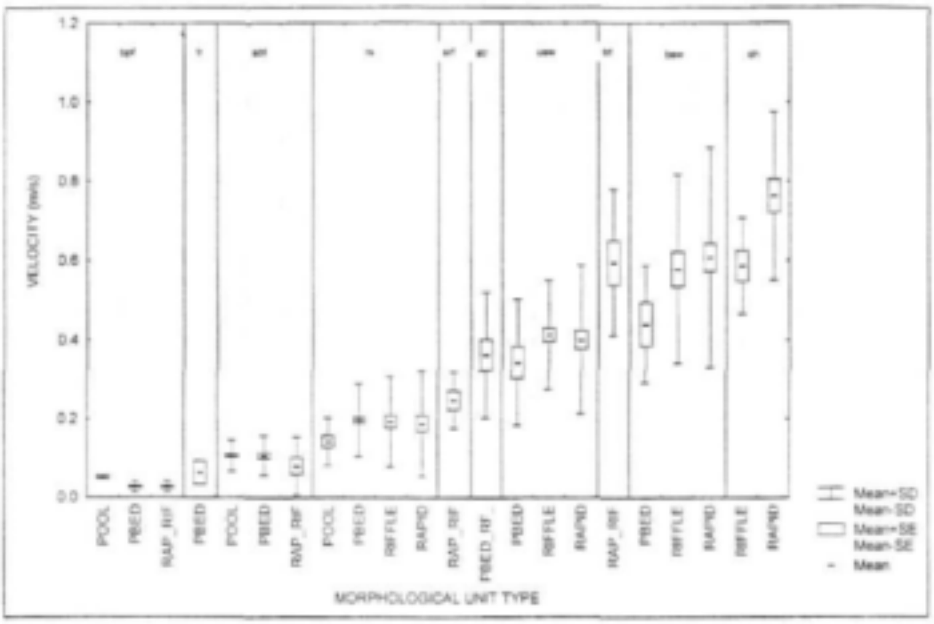


Figure 8.12b : Velocity characteristics of flow types

It indicates a consistent increase in flow velocity, in both magnitude and variability, from the less turbulent biotope classes (pool, glide, run) and flow types (barely perceptible flow, trickle and smooth boundary turbulent) to the more turbulent biotopes (riffle, rapid and chute) and flow types (undular and broken standing waves and chutes). It also shows that, in the case of pool, glide and run biotopes, the velocity characteristics vary only slightly depending on the type of morphological unit, while, in the case of riffle, rapid and chute biotopes, both the mean value and the variability of flow velocity differ significantly depending on the type of morphological unit. A similar pattern is observed in the case of flow types, with undular standing wave, broken standing wave and chute flow types displaying different velocity characteristics in different types of morphological units. This suggests that the velocity characteristics of these biotope classes and flow types are not independent of, but related to, the type of morphological unit.

Figure 8.13 a, which shows the flow depth characteristics associated with the various biotope classes, indicates that the chute, rapid and riffle biotopes are associated with lower flow depths than the run, glide and pool biotopes. However, it also indicates that pool, glide and run biotope classes may occur at significantly different flow depths, depending on the morphological unit in which they are situated. Figure 8.13 b shows that the flow depths associated with the different flow types are very dependent on the type of morphological unit in which it occurs. It indicates that similar flow types are characterized by lower flow depths when occurring in riffle or rapid morphological units, as opposed to pool or plane bed morphological units.

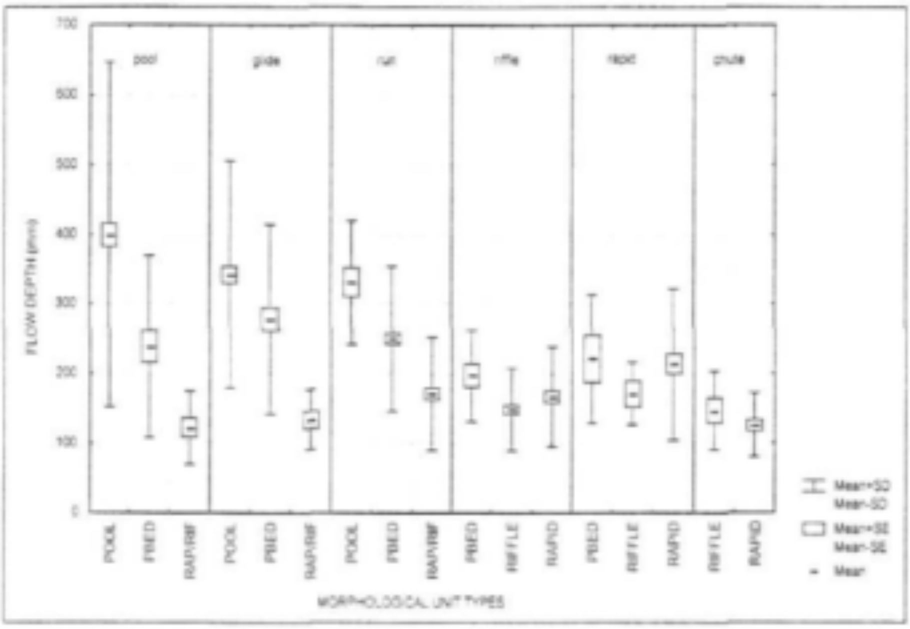


Figure 8.13a : Flow depth characteristics of biotope classes

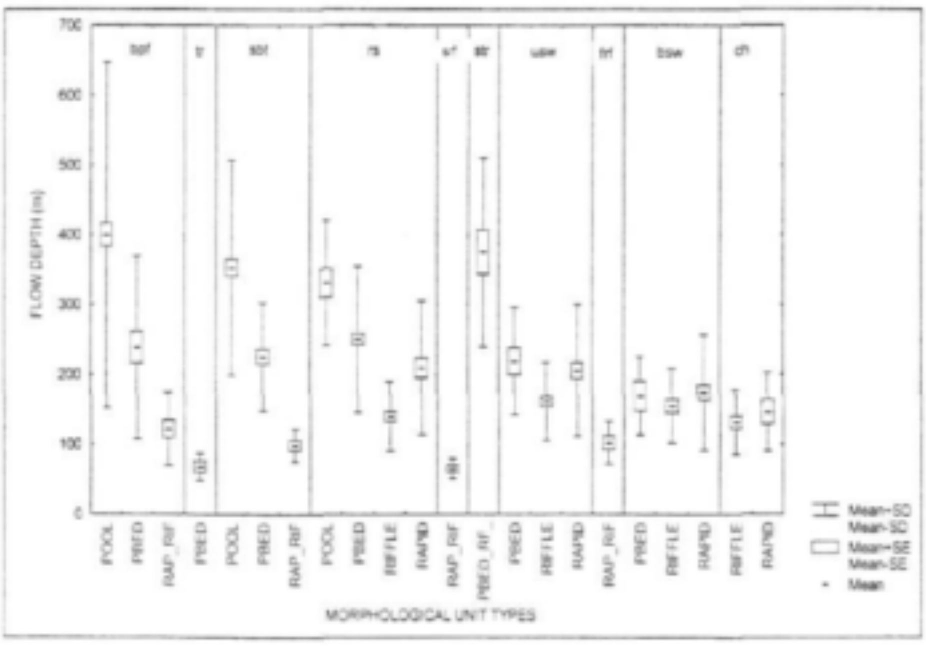


Figure 8.13b : Flow depth characteristics of flow types

Finally, the Froude number and velocity/depth ratio characteristics of the various biotope classes and flow types are shown in Figures 8.14 and 8.15. They display a steady increase in magnitude and variability from the less turbulent biotope classes and flow types to the more turbulent ones. It is also interesting to note that in the case of run, riffle, rapid and chute biotopes as well as in the case of undular and broken standing wave and chute flow types, the Froude number and V/D ratio exhibit significantly different values depending on the type of morphological unit. This again suggests that the hydraulic biotope classes and flow types are not independent of the type of morphological unit in which they occur.

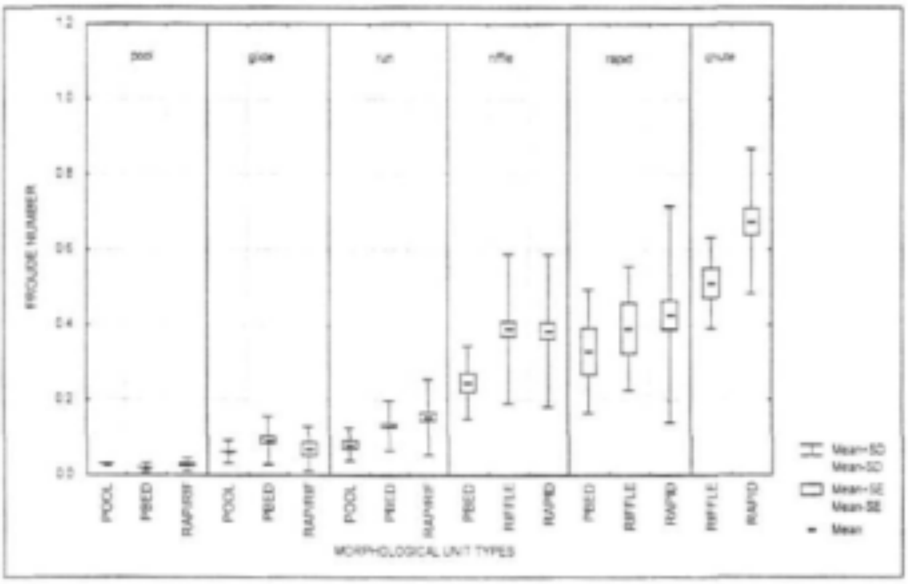


Figure 8.14a : Froude number characteristics of biotope classes

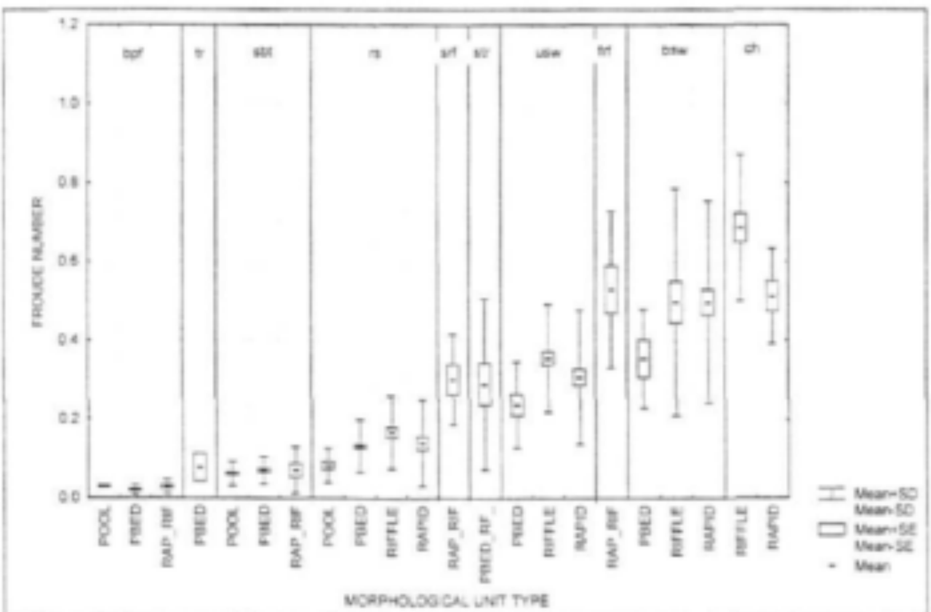


Figure 8.14b : Froude number characteristics of flow types

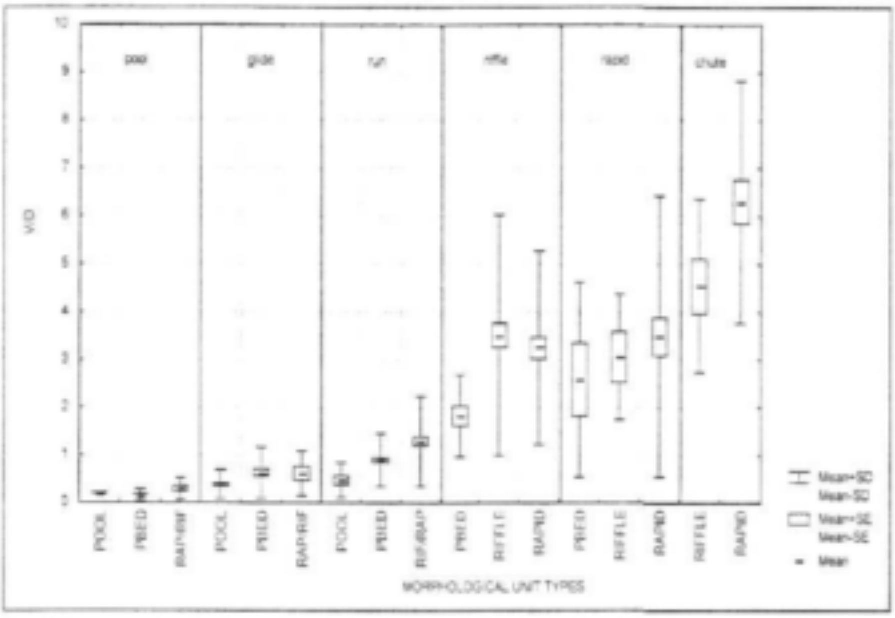


Figure 8.15a : Velocity/depth ratios of biotope classes

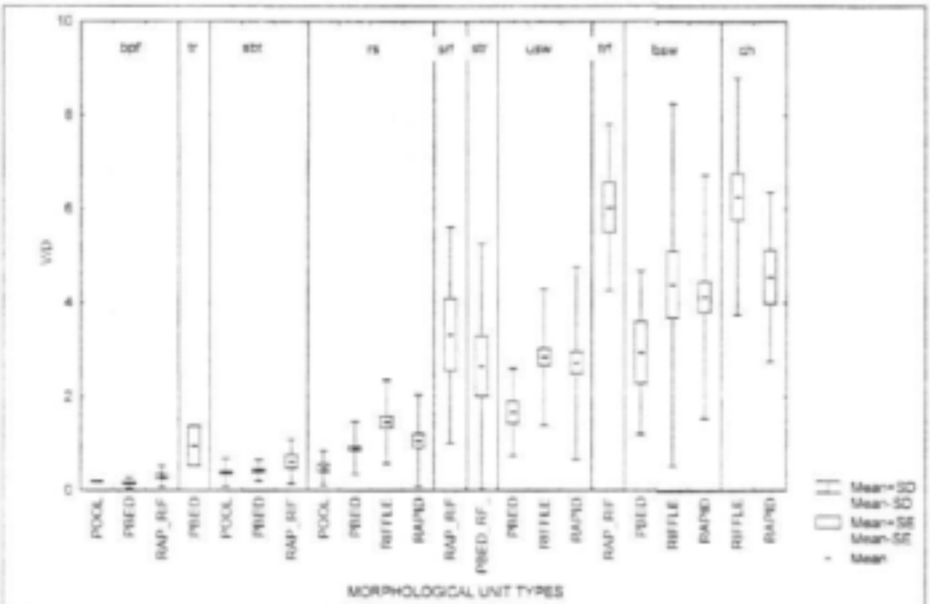


Figure 8.15b : Velocity/depth ratios of flow types

8.5 Conclusion

In essence, Chapter 8 addressed the characteristics of the physical habitat as determined by local hydraulic conditions. It was found that the average hydraulic conditions within cobble and boulder bed rivers are inadequate for representing the diversity of local hydraulic conditions within a reach. Not only are reaches characterized by different types of morphological units, each associated with unique hydraulic characteristics, but, due to the effect of large scale roughness, the hydraulic conditions within each morphological unit also vary considerably. Furthermore, it can be concluded that the dominant morphological unit types in cobble and boulder bed rivers of the Western Cape, i.e. pool, plane bed, rapid and riffle morphological units, display significant variability in terms of their habitat diversity, with rapid and riffle morphological units characterized by a wider range of hydraulic biotope classes and flow types, than plane bed and pool morphological units. Finally, it was demonstrated that different biotope classes and flow types may be classified in terms of their hydraulic characteristics. However, it was found that similar biotope classes and flow types display different hydraulic characteristics depending on the type of morphological unit in which they are situated. This implies that the hydraulic classification of habitat types in cobble and boulder bed rivers needs to accommodate the type of morphological unit in which it is situated.

9. THE PROBABILITY DISTRIBUTION OF LOCAL VELOCITIES IN COBBLE AND BOULDER BED RIVERS

9.1 Introduction

The description of the aquatic habitat in freshwater ecosystems requires information on the spatial variability of hydraulic conditions within a reach, which bridges the gap between the reach scale, which is appropriate for a reliable simulation of average hydraulic conditions, and the local scale, at which habitat preferences occur. This is of particular importance in cobble and boulder bed rivers, where the effect of large-scale roughness is dominant and complex flow patterns occur, especially during low flows. The previous chapter clearly showed that the average hydraulic conditions within cobble and boulder bed reaches do not represent the diversity of hydraulic conditions present in these reaches, especially during low flows. It was found that, not only are reaches characterized by different types of morphological units, each associated with unique hydraulic characteristics, but, due to the effect of large scale roughness, the hydraulic conditions within each morphological unit also vary considerably.

As shown in Chapter 7, most research on intermediate to large scale roughness in cobble and boulder bed rivers have focused on estimating the average resistance, which is subsequently used to calculate the relationship between the mean velocity and the average flow depth under the assumption of uniform flow. However, due to the complex nature of flow patterns under conditions of large scale roughness in cobble and boulder bed rivers, this provides no information on the spatial distribution of local velocities within the reach under consideration. The statistical description of the velocity distribution under these conditions is therefore an attractive alternative.

Dingman (1989) investigated the probability distribution of flow velocities in channel cross sections. From existing hydraulic and statistical relationships for idealized channel cross sections, he derived the following power-law to define the probability distribution of velocities in natural channel cross sections:

$$F(v) = \left(\frac{v}{V_{max}}\right)^{j} \qquad (9.1)$$

with v : local flow velocity

V_{max} : maximum velocity in cross section j : shape parameter

With the aid of field measurements, Dingman confirmed that the velocity distribution in natural channel cross sections is well characterized by the power-law distribution over a wide range of stream types and conditions, including large and intermediate scale roughness. However, he failed to relate the distribution parameters V_{max} and j to any explanatory variables.

A more practical model was developed by Lamouroux *et al.* (1995), who analyzed velocity data on several French stream segments with intermediate to large scale roughness statistically. The frequency distribution of point velocities relative to the mean velocity, was expressed as a combination of a centered (Gaussian) model, grouped around the mean, and a decentered (Gaussian and exponential) model. A shape parameter, describing the point velocity frequency distribution, was defined and dimensional analysis was used to model this parameter, and subsequently the velocity distribution, as a function of average parameters within the reach, e.g. roughness, flow depth and flow width.

Given the relative simplicity of the Lamouroux model in terms of input data requirements, as well as the important link between the reach scale (average cross-sectional hydraulic parameters) and the local scale (point velocities), a similar approach was adopted in this research programme to predict the velocity distribution of local flow velocities in cobble and boulder bed rivers of the Western Cape during low flows. However, as these rivers are characterized by different types of morphological units, each associated with unique velocity characteristics, a distinction was made between the three dominant types of morphological units, viz. (1) pools, (2) plane beds and (3) rapids and riffles. The randomly measured point velocities (v) within a morphological unit was expressed as "relative velocities" defined as the ratio $\frac{v}{V}$, with V the average, cross-sectional velocity within the cross section representing the morphological unit. (The value of V was determined by dividing the discharge, as calculated from the velocity-area method, by the flow area). Probability distributions were then fitted to the observed data and relationships identified between the statistical parameters and average hydraulic parameters of the different data sets within each of the three main morphological unit types. (In some instances, relative velocities from similar morphological unit types within the same reach were combined, e.g. from two pools or from two riffles. This was done to provide a larger data set for the subsequent statistical analyses. However, the criterion was that the cross-sections must display similar average hydraulic parameters.)

Table 9.1 lists the data sets as used in the subsequent statistical analyses.

REACH	CROSS SECTION NUMBERS
POOLS	
Whitebridge	2, 5
Berg I	5
Jonkershoek	1, 6
Du Toits	1
Du Toits	3
Berg II	2, 4
Elands	5, 6
Vergenoeg	1, 2
Molenaars	3
Vlottenburg	1
PLANE BEDS	
Whitebridge	3
Berg I	1, 2
Jonkershoek	2
Jonkershoek	3
Du Toits	2
Elands	1, 2
Vergenoeg	5, 6
Berg II	3
Molenaars I	2
RIFFLES & RAPIDS	
Whitebridge	4
Whitebridge	1
Berg I	3, 4
Jonkershoek	5
Berg II	1, 5
Elands	3, 4
Vergenoeg	3
Vergenoeg	4
Molenaars I	1
Vlottenburg	2, 3
Du Toits	4
Du Toits	5

Table 9.1 : Data sets for statistical analyses

9.2 Distribution fitting

Appendix J shows the observed frequency distributions of relative velocity for each data set. Generally, they are skewed distributions, which in some cases display extreme values. To identify probability distribution(s) that could be used to predict the frequency distribution of relative velocities in cobble and boulder bed rivers, a broad spectrum of probability distribution types were fitted to the observed data. These include the Normal, Log-normal, Extreme type I, Gamma, Rayleigh and Weibull distributions and represent centered, decentered and extreme type distributions. (Table 9.2 lists these distributions and their relevant parameters.)

As a preliminary process of elimination, probability plots were utilized to visually identify those distributions which display a poor fit of the observed data These were then eliminated from further analyses for that particular data set. The next step involved goodness-of-fit tests to test the validity of the assumed distributions. The Chi-square and Kolmogorov-Smirnov tests were used to determine the absolute statistical significance as well as the relative goodness-of-fit for each of the theoretical probability distributions. (The results of these tests are found in Table 9.3) Generally, the results confirm that in almost all cases, all the probability distributions which were evaluated, are statistically significant at a significance level of α = 5%. Based on these results, the relative goodness-of-fit of the various distributions could then be determined. Consequently, it was concluded that:

- within most of the pool morphological units, the Weibull distribution consistently provides the best estimate of the frequency distribution of relative point velocities.
- within plane bed morphological units, the Extreme and Weibull distributions both display the best fit to the observed data, relative to the other distributions.
- within rapid- and riffle morphological units in general, the Extreme distribution displays the best fit to the observed data, followed by the Weibull distribution.

Normal distribution

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2} \qquad -\infty < x < \infty$$

μ : mean

σ : standard deviation

Log-normal distribution

$$f(x) = \frac{1}{\sqrt{2\pi}\beta} x^{-1} e^{-(\ln x-\alpha)^2/2\beta^2} \qquad x > 0 \,;\, \beta > 0$$

α : scale parameter

β : shape parameter

Extreme Type I distribution

$$f(x) = \alpha \exp\left[-\alpha(x-\beta) - e^{-\alpha(x-\beta)}\right] \qquad -\infty < x < \infty$$

α : scale parameter

β : location parameter

Gamma distribution

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad x > 0 \,;\, \alpha > 0;\, \beta > 0$$

α : shape parameter

β : scale parameter

Rayleigh distribution

$$f(x) = \frac{x}{\beta^2} e^{-x^2/2b^2} \qquad 0 \le x < \infty \,;\, \beta > 0$$

β : scale parameter

Weibull distribution

$$f(x) = \alpha\beta x^{\beta-1} e^{-\alpha x^{\beta}} \qquad x > 0 \,;\, \alpha > 0 \,;\, \beta > 0$$

α : scale parameter

β : shape parameter

Table 9.2 : Probability distribution types which were considered

STYDY REACH		NORMAL		LOGN		GAMMA		EXTREME		RAYLEIGH		WEIBULL	
Cross section(s)		Chi^2	Kol-Smv.	Chi^2	Kol-Smv.	Chi^2	Kol-Smv.	Chi^2	Kol-Smv.	Chi^2	Kol-Smv.	Chi^2	Kol-Smv.
	n	$\sum_{i=1}^{k}\frac{(n_i-e_i)^2}{e_i}$	D_n (max)	$\sum_{i=1}^{k}\frac{(n_i-e_i)^2}{e_i}$	D_n (max)	$\sum_{i=1}^{k}\frac{(n_i-e_i)^2}{e_i}$	D_n (max)	$\sum_{i=1}^{k}\frac{(n_i-e_i)^2}{e_i}$	D_n (max)	$\sum_{i=1}^{k}\frac{(n_i-e_i)^2}{e_i}$	D_n (max)	$\sum_{i=1}^{k}\frac{(n_i-e_i)^2}{e_i}$	D_n (max)
POOLS													
Whitebridge (XS 5 & 2)	48	**3.40**	**0.11**	-	**0.15**	**1.90**	**0.13**	**2.20**	**0.14**	**1.00**	**0.12**	**1.00**	**0.12**
Berg I (XS 5)	40	32.20	0.24	22.10	0.27	20.30	0.26	25.30	0.27	32.50	0.30	14.60	0.23
Jonkershoek (XS 1 & 6)	48	**4.60**	**0.14**	**5.10**	**0.14**	**2.00**	**0.12**	**2.00**	**0.15**	**1.20**	**0.19**	**1.30**	**0.13**
Du Toits (XS 1)*	20	-	**0.15**	-	**0.16**	-	**0.14**	-	**0.13**	-	**0.18**	-	**0.13**
Du Toits (XS 3)*	24	-	**0.17**	-	**0.19**	-	**0.19**	-	**0.18**	-	**0.31**	-	**0.19**
Berg II (XS 2 & 4)	46	19.40	**0.16**	10.60	**0.11**	7.40	**0.10**	12.00	**0.11**	21.10	0.21	6.70	**0.09**
Elands (XS 5 & 6)	56	12.90	**0.15**	23.10	**0.14**	13.00	**0.12**	13.60	**0.12**	-	0.20	10.00	**0.11**
Vergenoeg (XS 1 & 2)	51	**3.90**	**0.11**	**4.20**	**0.11**	**2.20**	**0.09**	**2.70**	**0.09**	**0.70**	**0.07**	**1.20**	**0.09**
Molenaars (XS 3)	49	**3.50**	**0.08**	6.30	**0.18**	**3.20**	**0.15**	**3.10**	**0.13**	**1.90**	**0.12**	**2.20**	**0.11**
Vlottenburg (XS 1)	33	9.80	**0.12**	11.20	**0.22**	7.60	**0.18**	8.00	**0.15**	8.70	**0.16**	7.00	**0.15**
PLANE BEDS													
Whitebridge (XS 3)*	22	-	**0.15**	-	**0.10**	-	**0.11**	-	**0.12**	-	**0.12**	-	**0.12**
Berg I (XS 1 & 2)	51	12.00	**0.09**	29.60	0.23	15.50	0.19	13.10	**0.15**	11.90	**0.15**	11.20	**0.17**
Jonkershoek (XS 2)*	21	-	**0.20**	-	**0.13**	-	**0.16**	-	**0.19**	-	0.39	-	**0.16**
Jonkershoek (XS 3)*	24	-	**0.10**	-	**0.14**	-	**0.09**	-	**0.09**	-	**0.13**	-	**0.08**
Du Toits (XS 2)*	23	-	**0.17**	-	**0.12**	-	**0.09**	-	**0.10**	-	**0.22**	-	**0.11**
Elands (XS 1 & 2)	48	**4.00**	**0.12**	-	**0.14**	**1.90**	**0.10**	**2.10**	**0.10**	**1.80**	**0.10**	**0.90**	**0.09**
Vergenoeg (XS 5 & 6)	44	**2.70**	**0.08**	-	**0.16**	-	**0.12**	**4.40**	**0.10**	**2.40**	**0.11**	**2.60**	**0.09**
Berg II (XS 3)	39	**2.80**	**0.11**	9.40	**0.18**	**2.80**	**0.13**	**1.00**	**0.07**	**0.10**	**0.09**	**1.10**	**0.09**
Molenaars (XS 2)	44	**7.10**	**0.09**	-	**0.15**	**4.40**	**0.11**	**5.00**	**0.11**	**4.80**	**0.10**	**4.10**	**0.10**
RAPIDS and RIFFLES													
Whitebridge (XS 4)*	19	-	**0.17**	-	**0.23**	-	**0.20**	-	**0.18**	-	**0.28**	-	**0.18**
Whitebridge (XS 1)*	20	-	**0.12**	-	**0.20**	-	**0.14**	-	**0.09**	-	**0.15**	-	**0.11**
Berg I (XS 3 & 4)	54	**10.20**	**0.09**	**3.00**	**0.12**	**1.20**	**0.09**	**3.10**	**0.07**	**4.90**	**0.12**	**1.80**	**0.06**
Jonkershoek (XS 5)*	22	-	**0.15**	-	**0.19**	-	**0.17**	-	**0.16**	-	**0.29**	-	**0.17**
Du Toits (XS 4)*	23	-	**0.15**	-	**0.13**	-	**0.12**	-	**0.14**	-	**0.20**	-	**0.12**
Du Toits (XS 5)	39	22.50	**0.13**	**4.50**	**0.15**	**3.90**	**0.12**	13.00	**0.12**	33.50	0.26	**3.90**	**0.11**
Berg II (XS 1 & 5)	49	**6.20**	**0.09**	13.70	0.23	**4.00**	**0.17**	**2.90**	**0.12**	**4.80**	**0.17**	**1.80**	**0.14**
Elands (XS 3 & 4)	55	7.60	**0.11**	**3.20**	**0.09**	**2.50**	**0.07**	**3.70**	**0.08**	**3.10**	**0.11**	**2.60**	**0.08**
Vergenoeg (XS 3)*	23	-	**0.08**	-	**0.20**	-	**0.16**	-	**0.14**	-	**0.15**	-	**0.13**
Vergenoeg (XS 4)*	21	-	**0.15**	-	**0.18**	-	**0.13**	-	**0.11**	-	**0.12**	-	**0.12**
Molenaars (XS 1)	48	**6.10**	**0.14**	-	**0.15**	**2.40**	**0.10**	**2.40**	**0.07**	**2.80**	**0.13**	**1.60**	**0.07**
Vlottenburg (XS 2 & 3)	49	**6.30**	**0.09**	-	**0.16**	-	**0.11**	9.10	**0.10**	-	**0.10**	**6.00**	**0.10**

* Chi-square test inaccurate due to ($k<5$) and/or ($e_i<5$)

Note: Bold values indicate statistical significance at the 5% level.

Table 9.3 : Goodness-of-fit-tests results

9.3 Parameter estimates

Having identified the most suitable probability distributions for predicting the frequency distribution of relative velocity in cobble and boulder bed reaches, the statistical parameters describing these distributions needed to be related to one or more explanatory variables. The following hydraulic parameters were selected as possible explanatory variables:

- Froude number
- velocity/depth ratio
- Reynolds number
- relative submergence (D/d_{50} or D/d_{84})
- width/depth ratio

The first two parameters were selected because of their significant variation between pool, plane bed and riffle or rapid morphological units as evident from Chapter 8. The kinematic viscosity of water changes gradually with temperature and therefore it was assumed that the Reynolds number is directly related to the discharge per unit width (the product of flow velocity and depth), thus providing an indication of the magnitude of flow. At a given slope, the unit discharge as well as the power being released by the stream are thus represented by the Reynolds number. The relative submergence was included because of its relationship to flow resistance in cobble and boulder bed rivers under conditions of large-scale roughness. Finally, the effect of channel shape, may be described by the ratio of flow width to flow depth (W/D).

Simple and multiple linear regression techniques were used to investigate the relationships between the statistical parameters of the probability distributions and the relevant explanatory variables. (Since the parameters, which define the Weibull and Extreme probability distributions, may be estimated from the sample mean and variance, the sample mean (μ) and standard deviation (σ) were also included as dependent variables.)

Table 9.4 lists the average hydraulic parameters for each data set, along with the relevant statistical parameters.

	STATISTICAL PARAMETERS						EXPLANATORY VARIABLES					
			Weibull		Extreme							
POOLS	**Mean**	**St. Dev.**	**Scale**	**Shape**	**Location**	**Scale**	**Fr**	**V/D**	**W/D**	**D/d_{50}**	**D/d_{84}**	**Re**
Whitebridge (XS 5 & 2)	1.247	0.678	1.412	1.977	-	-	0.045	0.289	21.458	1.200	0.470	1.650
Jonkershoek (XS 1 & 6)	1.044	0.638	1.169	1.684	-	-	0.050	0.283	16.113	1.450	0.620	2.700
Du Toits (XS 1)	1.517	0.964	1.698	1.646	-	-	0.019	0.122	23.971	1.500	0.550	0.630
Du Toits (XS 3)	1.552	1.285	1.636	1.162	-	-	0.033	0.265	33.613	1.040	0.380	0.650
Berg II (XS 2 & 4)	1.115	0.822	1.225	1.394	-	-	0.035	0.186	19.574	2.050	0.700	2.350
Elands (XS 5 & 6)	0.772	0.506	0.856	1.530	-	-	0.042	0.215	36.127	1.370	0.750	3.000
Vergenoeg (XS 1 & 2)	1.112	0.572	1.260	2.090	-	-	0.040	0.231	20.560	2.500	0.850	2.150
Molenaars (XS 3)	1.063	0.538	1.196	2.066	-	-	0.063	0.412	95.868	1.750	0.760	2.140
Vlottenburg (XS 1)	0.949	0.529	1.061	1.800	-	-	0.017	0.053	14.685	7.286	4.435	5.860
PLANE BEDS												
Whitebridge (XS 3)	1.194	0.684	1.354	1.910	0.890	0.499	0.160	1.385	27.574	0.650	0.260	2.360
Berg I (XS 1 & 2)	1.200	0.745	1.318	1.511	0.838	0.659	0.059	0.423	28.502	0.800	0.390	1.670
Jonkershoek (XS 2)	1.084	1.091	1.045	0.926	0.605	0.736	0.119	0.800	16.118	1.000	0.430	3.770
Jonkershoek (XS 3)	1.303	0.851	1.443	1.544	0.911	0.679	0.067	0.405	16.280	1.260	0.540	2.990
Du Toits (XS 2)	1.300	1.019	1.434	1.396	0.880	0.662	0.088	0.740	17.021	0.930	0.340	1.430
Elands (XS 1 & 2)	1.139	0.647	1.276	1.796	0.828	0.555	0.100	0.616	38.494	0.970	0.530	4.150
Vergenoeg (XS 5 & 6)	1.174	0.557	1.322	2.251	0.899	0.515	0.113	0.860	27.500	1.500	0.550	2.700
Berg II (XS 3)	1.078	0.651	1.198	1.651	0.777	0.534	0.188	1.389	26.833	1.060	0.370	4.500
Molenaars (XS 2)	1.209	0.647	1.361	1.948	0.895	0.569	0.110	0.777	79.677	1.500	0.650	3.000
RAPIDS and RIFFLES												
Whitebridge (XS 4)	1.141	0.845	1.215	1.232	0.740	0.696	0.350	2.833	16.000	0.750	0.290	6.400
Whitebridge (XS 1)	1.334	0.917	1.450	1.389	0.913	0.729	0.284	2.507	17.120	0.630	0.250	3.950
Berg I (XS 3 & 4)	1.458	0.915	1.620	1.605	1.036	0.723	0.261	2.186	35.714	0.510	0.250	4.300
Jonkershoek (XS 5)	1.469	1.238	1.491	1.041	0.903	0.948	0.301	2.560	20.632	0.630	0.270	4.700
Berg II (XS 1 & 5)	1.220	0.816	1.313	1.334	0.835	0.690	0.289	2.497	27.465	0.780	0.270	4.350
Elands (XS 3 & 4)	1.441	0.825	1.629	1.860	1.060	0.646	0.214	1.598	53.056	0.650	0.360	4.900
Vergenoeg (XS 3)	1.179	0.552	1.316	2.203	0.909	0.517	0.396	4.258	51.142	0.650	0.230	3.100
Vergenoeg (XS 4)	1.104	0.650	1.244	1.819	0.813	0.503	0.272	2.279	21.429	1.080	0.370	4.470
Molenaars (XS 1)	1.336	0.807	1.490	1.679	0.963	0.646	0.270	2.589	150.400	0.820	0.350	2.930
Vlottenburg (XS 2 & 3)	0.908	0.426	1.021	2.261	0.694	0.406	0.314	2.247	63.700	1.360	0.830	8.300
Du Toits (XS 4)	1.515	1.029	1.673	1.494	1.048	0.774	0.214	2.375	46.875	0.530	0.200	1.500
Du Toits (XS 5)	1.318	1.060	1.399	1.199	0.839	0.787	0.181	1.789	48.402	0.670	0.250	1.800

Table 9.4 : Statistical parameters and relevant explanatory variables

The approach that was followed during regression analyses is as follows:

- Scatterplots were used to identify relationships between all pairs of variables. If outliers were identified, the calculations were checked and corrected if possible. If the data could not be corrected, the data set was rejected.
- A correlation matrix was calculated to identify the correlation coefficients. (Although it is realized that a low correlation coefficient does not imply that the variable will not be a useful predictor in the case of multiple regression.)
- Regression equations were fitted, which define each of the statistical parameters as a function of one or more explanatory variables.

In the case of both simple and multiple linear regression, the *t*-distribution was used to test the statistical significance of the respective regression coefficients, while the ANOVA *F*-test was used as an additional significance test in the case of multiple linear regression.

9.3.1 Pool morphological units

Table 9.5 shows the correlation between the different variables. (The shaded values indicate the dependent variables.) It shows that both the mean and standard deviation display good correlation with the relative submergence (D/d_{84}) and Reynolds number, while only the scale parameter (α_{WB}) of the Weibull distribution shows any significant relationship to any explanatory variable – in this case the Reynolds number.

	Fr	V/D	W/D	D/d_{50}	D/d_{84}	Re	μ	σ	α_{WB}	β_{WB}
Fr	1.00									
V/D	**0.92**	1.00								
W/D	0.62	**0.72**	1.00							
D/d_{50}	0.07	-0.11	-0.01	1.00						
D/d_{84}	0.37	0.08	0.25	**0.81**	1.00					
Re	0.60	0.24	0.06	0.35	0.71	1.00				
μ	-0.59	-0.25	-0.17	-0.31	**-0.74**	**-0.97**	1.00			
σ	-0.64	-0.33	-0.24	-0.43	**-0.77**	**-0.82**	**0.87**	1.00		
α_{WB}	-0.58	-0.26	-0.18	-0.26	-0.70	**-0.97**	**0.99**	**0.80**	1.00	
β_{WB}	0.52	0.43	0.31	0.45	0.50	0.25	-0.30	**-0.72**	-0.20	1.00

Table 9.5 : Correlation coefficients : Pool morphological units (Bold values are statistically significant at $p < 0.05$)

The following regression equations were subsequently calculated: (The 95 % confidence intervals of the regression coefficients are provided in brackets, while the r^2 value and the statistical significance are also indicated.)

i. Mean and standard deviation

Mean (μ)

Equation : $\mu = 1.722\ (\pm 0.139) - 0.285\ (\pm 0.069)\ Re$ (9.2a)

r^2 : *0.95*

Stat. Significance : $\alpha = 5\%$

Standard deviation (σ)

Equation : $\sigma = 1.224\ (\pm 0.355) - 0.248\ (\pm 0.171)\ Re$ (9.2b i)

r^2 : *0.68*

Stat. Significance : $\alpha = 5\%$

Equation : $\sigma = 1.272\ (\pm 0.411) - 43.62\ (\pm 24.54)\ Fr + 5.04\ (\pm 3.72)\ V/D$ (9.2b ii)

r^2 : *0.81*

Stat. Significance : $\alpha = 5\%$

ii. Weibull distribution

Scale (α) Parameter

Equation : $\alpha = 1.877\ (\pm 0.162) - 0.299\ (\pm 0.078)\ Re$ (9.3a)

r^2 : *0.936*

Stat. Significance : $\alpha = 5\%$

Shape (β) Parameter

Equation : $\beta = 1.556\ (\pm 0.732) + 241.262\ (\pm 191.18)\ Fr - 28.54\ (\pm 23.95)\ V/D$
$- 1.351\ (\pm 1.143)\ Re$ (9.3b)

r^2 : *0.767*

Stat. Significance : *F*-test p-value > 5 %

These regression equations show that in the case of pool morphological units, the mean and standard deviation of the relative velocity distribution can be related to either the Reynolds number or the Froude number and velocity-depth ratio at a significance level of $\alpha = 5\%$ and with relatively high r^2 values. However, although the scale parameter of the Weibull distribution shows a good correlation to the Reynolds number, the Weibull shape parameter can not be significantly expressed as a function of any explanatory variable.

9.3.2 Plane bed morphological units

Table 9.6 shows that there is no significant correlation between any of the dependent and explanatory variables in the case of plane bed morphological units. This was confirmed during the regression analyses, which resulted in no statistically significant regression equations for estimation of the statistical parameters. This might be attributed to various factors. Firstly, whereas pools, riffles and rapids are fairly easy to identify visually, plane beds are not, and this might have led to morphological units being classified as plane bed morphological units, while they are in actual fact not. Secondly, the frequency distribution of point velocities within plane beds might be related to other explanatory variables which were not considered, e.g. local energy gradient, standard deviation of bed particle size, etc.

	Fr	V/D	W/D	D/d_{50}	D/d_{84}	Re	μ	σ	α_{WB}	β_{WB}	β_{EXT}	α_{EXT}
Fr	1.00											
V/D	**0.96**	1.00										
W/D	0.15	0.07	1.00									
D/d_{50}	-0.15	-0.26	0.45	1.00								
D/d_{84}	-0.27	-0.46	0.60	**0.89**	1.00							
Re	0.24	-0.05	0.19	0.27	0.52	1.00						
μ	-0.45	-0.25	-0.10	0.09	-0.06	-0.63	1.00					
σ	-0.18	-0.17	-0.55	-0.32	-0.38	-0.09	0.08	1.00				
α_{WB}	-0.29	-0.10	0.12	0.13	0.02	-0.57	**0.91**	-0.32	1.00			
β_{WB}	0.27	0.31	0.48	0.41	0.33	-0.05	0.11	**-0.93**	0.49	1.00		
β_{EXT}	-0.13	0.02	0.28	0.24	0.14	-0.45	**0.73**	-0.61	**0.94**	**0.75**	1.00	
α_{EXT}	-0.56	-0.59	-0.43	-0.12	-0.08	-0.03	0.08	**0.87**	-0.31	**-0.92**	-0.59	1.00

Table 9.6 : Correlation coefficients : Plane bed morphological units (Bold values are statistically significant at $p < 0.05$)

9.3.3 Rapid- and riffle morphological units

From Table 9.7 it is observed that all the statistical parameters display a statistically significant correlation with relative submergence (either D/d_{50} or D/d_{84}). In some cases there is also good correlation with the Reynolds number.

	Fr	V/D	W/D	D/d_{50}	D/d_{84}	Re	μ	σ	β_{EXT}	α_{EXT}	α_{WB}	β_{WB}
Fr	1.00											
V/D	**0.87**	1.00										
W/D	-0.06	0.07	1.00									
D/d_{50}	0.06	-0.22	0.11	1.00								
D/d_{84}	0.10	-0.22	0.23	**0.86**	1.00							
Re	0.40	-0.08	-0.20	**0.63**	**0.76**	1.00						
μ	-0.33	-0.08	0.07	**-0.88**	**-0.68**	**-0.62**	1.00					
σ	-0.34	-0.18	-0.18	**-0.73**	**-0.64**	-0.49	**0.82**	1.00				
β_{EXT}	-0.28	0.00	0.25	**-0.76**	-0.54	**-0.58**	**0.88**	0.46	1.00			
α_{EXT}	-0.22	-0.08	-0.19	**-0.76**	**-0.65**	-0.44	**0.80**	**0.99**	0.44	1.00		
α_{WB}	-0.37	-0.10	0.15	**-0.84**	**-0.63**	**-0.63**	**0.97**	**0.68**	**0.96**	**0.65**	1.00	
β_{WB}	0.26	0.22	0.34	0.50	**0.58**	0.30	-0.49	**-0.86**	-0.05	**-0.87**	-0.32	1.00

Table 9.7: Correlation coefficients : Rapid- and riffle morphological units (Bold values are statistically significant at $p < 0.05$)

The following regression equations were calculated :

i. Weibull distribution

Scale (α) Parameter

Equation : $\alpha = 2.116\ (\pm 0.279) - 0.092\ (\pm 0.077)\ V/D + 0.002\ (\pm 0.002)\ W/D - 0.738\ (\pm 0.216)\ D/d_{50}$ (9.4a)

r^2 : *0.87*

Stat. Significance : $\alpha = 5\%$

Shape (β) Parameter

Equation : $\beta = 1.153\ (\pm 0.456) + 1.348\ (\pm 1.25)\ D/d_{84}$ (9.4b)

r^2 : *0.34*

Stat. Significance : $\alpha = 5\%$

ii. Extreme Type I distribution

Scale (α)

Equation : $u = 1.0\ (\pm 0.205) - 0.442\ (\pm 0.253)\ D/d_{50}$ (9.5a)

r^2 : *0.57*

Stat. Significance : $\alpha = 5\%$

<u>Location (β)</u>

Equation : $\alpha = 1.13\ (\pm 0.16) + 0.001\ (\pm 0.001)\ W/D - 0.38\ (\pm 0.19)\ D/d_{50}$ (9.5b i)

r^2 : *0.68*

Stat. Significance : Regression coefficient of W/D not significant at $\alpha = 5\%$

Equation : $\alpha = 1.167\ (\pm 0.169) - 0.360\ (\pm 0.207)\ D/d_{50}$ (9.5b ii)

r^2 : *0.57*

Stat. Significance : $\alpha = 5\%$

iii. Mean and standard deviation

<u>Mean (μ)</u>

Equation : $\mu = 1.99\ (\pm 0.264) - 0.076\ (\pm 0.073)\ V/D - 0.693\ (\pm 0.205)\ D/d_{50}$ (9.6a)

r^2 : *0.95*

Stat. Significance : $\alpha = 5\%$

<u>Standard deviation (σ)</u>

Equation : $\sigma = 1.659\ (\pm 0.480) - 0.719\ (\pm 0.372)\ D/d_{50}\ \_0.114\ (\pm 0.132)\ V/D$ (9.6b i)

r^2 : *0.66*

Stat. Significance : Regression coefficient of V/D not significant at $\alpha = 5\%$

Equation : $\sigma = 1.329\ (\pm 0.328) - 0.648\ (\pm 0.403)\ D/d_{50}$ (9.6b ii)

r^2 : *0.53*

Stat. Significance : $\alpha = 5\%$

Equations 9.5 (a and b ii) and 9.6 (a and b ii) suggest that both parameters of the Extreme Type I distribution, as well as the mean and standard deviation can be related to average hydraulic parameters at a significance level of 5 % and with relatively high r^2 values. However, although the scale parameter of the Weibull distribution shows a good correlation to several explanatory variables, the equation defining the shape parameter has a very low r^2 value (0.34).

9.4 Conclusions

Due to the spatial variability of local hydraulic conditions in cobble and boulder bed rivers and in light of the importance of this variability for the description of the aquatic habitat in freshwater ecosystems, a statistical model was developed for predicting the probability distribution of local flow velocities in cobble and boulder bed rivers during low flows.

It was demonstrated that the distribution of local sets of point velocities within pool, rapid and riffle morphological units may be related to average cross-sectional hydraulic parameters. The regression models which were subsequently developed, suggest that knowledge of the average velocity, flow depth, flow width and relative roughness within a cross section can be used to predict the frequency distribution of point velocity in these morphological units. For plane bed morphological units, no statistically significant relationships were found. This might be ascribed to inconsistent or inaccurate identification of plane bed morphological units, or suggests that the frequency distribution of point velocities within plane beds might be related to other explanatory variables which were not considered, e.g. the local energy gradient, the standard deviation of bed particle size, roughness concentration etc.

10. GUIDELINES FOR APPLICATION OF RESEARCH RESULTS

10.1 Introduction

In Chapter 1 it was envisaged that "tools" will be developed, that will describe the hydraulic and morphological characteristics of environmental flow components in cobble and boulder bed rivers of the Western Cape. Consequently, the results of this research programme include a combination of empirical, semi-empirical and theoretically-based hydraulic and morphological models which:

- describe the regime characteristics of cobble and boulder bed rivers
- predict the depth and rate of sand scouring in cobble beds
- calculate stage discharge relationships under conditions of large scale roughness
- predict the frequency distribution of local flow velocities in cobble and boulder bed rivers during low flows.

Although the development of these models has been described, no information has been provided on the application of these models. This chapter, therefore, aims to provide practical guidelines for the application of these models, which can be considered as rapid assessment tools for describing the hydraulic and morphological related characteristics of individual environmental flow components in cobble and boulder bed rivers of the Western Cape.

10.2 Predicting channel deformation in cobble and boulder bed rivers

10.2.1 Application

To predict the impact of a modified flow regime on macro scale morphology in cobble and boulder bed rivers. The model specifically addresses those morphological attributes which have special ecological significance, i.e. substrate characteristics, the local gradients of riffles and rapids, which affect turbulence, and the spacing or frequency of bed forms.

10.2.2 Relevant environmental flow component(s)

Channel forming flows

10.2.3 Model description

The model, which can be classified as a rational regime model, is based on the hypothesis that the formation of pools and riffles is essentially a mechanism of self-adjustment by the stream system towards obtaining dynamic equilibrium, i.e. at a characteristic discharge and bed particle size distribution, the river adjusts its width, average gradient, local gradient of the riffle or rapid, absolute roughness and flow depth until equilibrium exists, in terms of the power applied along the bed and the power required to suspend bed particles as well as in terms of momentum exchange between the accelerating water along the riffle and the slower moving water in the pool.

10.2.4 Procedure for application

Refer to Chapter 5

Known parameters: Bankfull discharge (Q_{bf}) ; Bed particle size distribution within the reach; Average channel gradient (S_0)

Deliverables: Local rapid / riffle gradient (α_r) ; Bed form length / spacing (L) ; Channel width (W_{ch})

i. Calculate the critical shear velocity (V^*_{cr}) from equation 5.21 based on representative particle diameters of d_{84} and d_{95} respectively:

$$V^*_{cr} = 0.12V_{ss} \qquad (5.21)$$

ii. Assume a value for bankfull channel width (W_{ch}) and calculate the values of the following variables :

- the critical flow depth, y_c (eq. 5.18)

$$y_c = \sqrt[3]{\frac{Q^2_{bf}}{gW_{ch}^{\ 2}}} \qquad (5.18)$$

- the shear velocity at the bed form crest , V^*_{crest} (eq. 5.17) at a flow depth of y_c

$$V^* = \sqrt{gyS_f} \qquad (5.17)$$

until $V^*_{crest} = (V^*_{cr})_{84}$

iii. Assume a value for the local gradient of the riffle or rapid (α_r) and calculate the values of the following variables:

- the normal flow depth, y_n (eq. 5.19)

$$Q_{bf} = y_n W_{ch} \sqrt{\frac{8gy_n S_f}{f}} \tag{5.19}$$

- the shear velocity along the riffle or rapid, $V^*_{riffle\text{-}rapid}$ (eq. 5.17) at a flow depth of y_n, until $V^*_{riffle\text{-}rapid} = (V^*_{cr})_{95}$

iv. From equations 5.7 to 5.16, calculate values of the bed form length/spacing (L).

10.3 A sand scour model for cobble bed rivers

10.3.1 Application

To determine the magnitude and the duration of flow, which is required to reach a certain level of sand scour in a cobble bed.

10.3.2 Relevant environmental flow component(s)

Sediment maintenance flow (Flushing flow)

10.3.3 Model description

Based on the law of conservation of stream power, a scour model was developed, which predicts the maximum depth of scour as well as the rate of scour of fine sands in a cobble bed. With the aid of physical model studies, distinct relationships were derived between the absolute roughness or maximum depth of scour, represented by Δ, sand particle characteristics and the relative applied power ($\frac{\sqrt{gDs}}{V_{ss}}$).

10.3.4 Procedure for application

Refer to Chapter 6

Known parameters: Average channel gradient (S_0 ; assume ≈ s) ; Characteristic sand particle diameter (d_{50}) ; Maximum required scour depth (k) (must be less than cobble diameter)

Deliverables: Required flow rate to reach specified scour level (Q) ; Duration until specified scour level is reached (t)

i. Assume a value for $\frac{\sqrt{gDs}}{V_{ss}}$ and calculate values for the following parameters:

- the flow depth, D (eq. 6.5)

$$\frac{\sqrt{gDs}}{V_{ss}} = \frac{1.6}{\frac{\sqrt{gDs}}{v}.d} \qquad (6.5)$$

- $\Delta = \left[\frac{\sqrt{gDs}\ .k}{\sqrt{2\pi}\ .v}\right]^{\frac{1}{2}}$

until the assumed value of $\frac{\sqrt{gDs}}{V_{ss}}$ and the calculated value of Δ correspond to the values as indicated on Figure 6.8. (The value of D represents the flow depth required to reach the specified scour depth and can be translated into a discharge.)

ii. Calculate the settling velocity of a sand particle under turbulent flow conditions from equation 6.7.

$$(V_{ss})_{TURB} = \sqrt{\frac{4(\rho_s - \rho)gd}{3\rho C_d}} \qquad (6.7)$$

iii. Select intermediate scour levels between the initial sand level and the required (maximum) scour level (Figure 10.1)

iv. From equation 6.12, calculate the turbulent applied stream power along the bed at each scour level, with the absolute bed roughness (k) at each level as indicated in Figure 10.1.

$$\text{Turbulent applied stream power} \approx \frac{30\rho gsD\sqrt{2\pi gsD}}{k} \qquad (6.12)$$

v. Calculate the ratio of turbulent applied power to settling velocity at each scour level and from Figure 6.7, determine the corresponding rate of scour (R_s) at each level.

vi. Calculate the time required to progress from one scour level (L_{s1}) to the next (L_{s2}) as follows:

$$t_{1\text{-}2} = [L_{s1} - L_{s2}] / \left[\frac{R_{s1} + R_{s2}}{2}\right] \qquad (10.1)$$

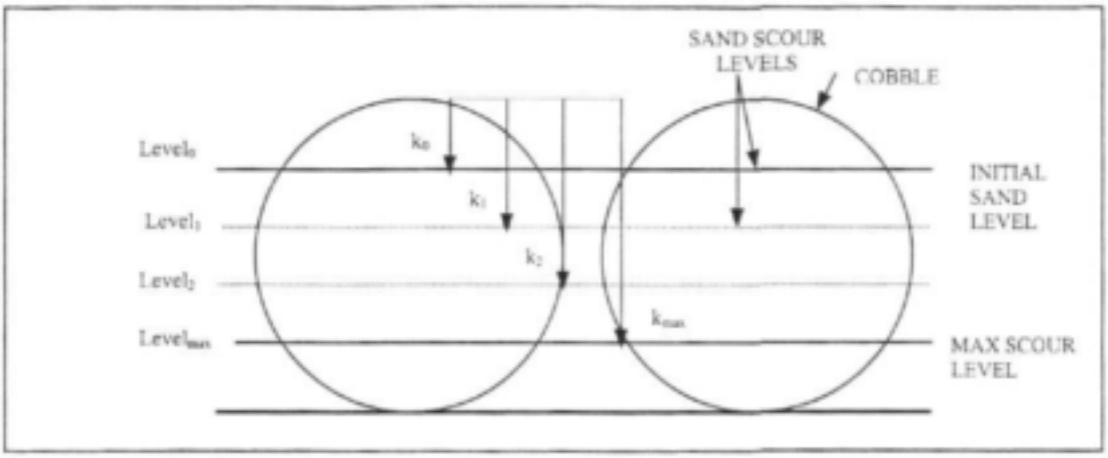


Figure 10.1 : Schematic diagram illustrating the progression of scour

10.4 Calculation of stage discharge relationships in cobble and boulder bed rivers

10.4.1 Application

To calculate stage discharge relationships under conditions of large scale roughness and uniform flow in cobble and boulder bed rivers.

10.4.2 Relevant environmental flow component (s)

Low flows, Freshes, Channel maintenance flows

10.4.3 Model description

A generally applicable, theoretically-based equation was developed for calculating stage discharge relationships in cobble and boulder bed rivers under conditions of large scale roughness.

10.4.4 Procedure for application

Refer to Chapter 7

Known parameters: Flow depth (or discharge)

Deliverables: Discharge (or flow depth)

i. With the Wolman sampling method determine the median particle diameter (d_{50}) within the reach.

ii. Survey the bed profiles of three cross sections within the reach as well as the average reach gradient (assumed equal to the water surface gradient).

iii. At the required water level (flow depth) calculate a reach-averaged hydraulic radius within each cross section.

iv. From equation 7.39 calculate the value of the large scale roughness resistance coefficient (C_x) within the reach, and from equation 7.41 calculate the discharge

$$C_x = 0.5285\left(\frac{R}{d_{50}}\right)^{-2.166} \tag{7.39}$$

$$Q = A\sqrt{\frac{2gd_{50}S_0}{C_x}} \tag{7.41}$$

10.5 Predicting the frequency distribution of point velocities in cobble and boulder bed rivers

10.5.1 Application

To relate the frequency distribution of point velocities at low flows in cobble and boulder bed rivers to average, cross sectional hydraulic parameters.

10.5.2 Relevant environmental flow component(s)

Low flows

10.5.3 Model description

The model distinguishes between pool and riffle or rapid morphological units and relates the statistical parameters of a relevant probability density function, describing the frequency distribution of point velocities within the morphological unit, to average cross section hydraulic parameters (e.g. flow velocity, flow depth, flow width and relative roughness).

10.5.4 Procedure for application

Refer to Chapter 9

Known parameters: Average flow velocity (V), flow depth (D) and flow width (W_T) within a representative cross section ; Characteristic bed particle diameters (d_{50} , d_{84})

Deliverables: Frequency distribution of point velocities (v) within a morphological unit.

i. From the known hydraulic parameters in the cross section, calculate the following variables: Froude number ($\frac{V}{\sqrt{gD}}$) , Reynolds number ($\frac{VD}{v}$) , Velocity/depth ratio (V/D) , Relative flow depth (D/d_{50}, D/d_{84}) , Width/depth ratio (W/D).

ii. Depending on the type of morphological unit represented by the cross section, calculate values for the relevant statistical parameters from the relevant regression equations in Chapter 9

iii. Calculate the frequency distribution of relative flow velocity (v/V) within the morphological unit from the relevant density function in Table 9.2

iv. Translate the relative flow velocities (v/V) to values of point velocity.

v. From Figures 8.12a and b, which classifies the different biotope classes and flow types in terms of their velocity characteristics, obtain an indication of habitat diversity within the morphological unit, in terms of biotope classes and flow type.

11. FINAL CONCLUSIONS AND RECOMMENDATIONS

11.1 Final conclusions

In essence, this research programme addressed the interaction between moving water and the physical attributes of cobble and boulder bed rivers, and as such provides a link between the macro scale morphological characteristics and the local (biotope) scale, ecologically significant hydraulic characteristics of these rivers. The objectives which were defined at the start of the research programme, have been met through the development of empirical, semi-empirical and theoretically based models, which define the hydraulic and morphological related characteristics of individual environmental flow components. These models, which may serve as tools for determining the hydraulic and morphological characteristics of individual environmental flow components in the cobble and boulder bed rivers of the Western Cape, mainly address:

- the regime characteristics of cobble and boulder bed rivers
- fine sand scouring in cobble beds
- stage-discharge relationships under conditions of large scale roughness, and
- low flow hydraulic characteristics of cobble and boulder bed rivers and their relationship to the aquatic habitat.

Practical guidelines for the application of these models have been developed.

The main conclusions that have been reached are:

- In the longitudinally concave-shaped, alluvial rivers of the Western Cape, cobble and boulder bed reaches typically occur in the mountain transitional zone, as well as in the upper and lower foothill zones. These reaches are characterized by four dominant types of morphologhical units, viz. pools, plane beds, riffles and rapids.
- The process of macro scale bed deformation in cobble and boulder bed rivers may be considered as a means of self adjustment towards obtaining dynamic equilibrium. The river bed transforms its profile into a series of consecutive macro scale bed forms in order to create natural control structures, each of which forces the water through critical depth with a subsequent hydraulic jump downstream. This deformation continues until equilibrium exists in terms of the power applied along the bed and the power required to suspend bed particles as well as in terms of momentum exchange

between the accelerating water along the riffle and the slower moving water in the pool.

- The process of scouring of fine sands in a cobble bed and the associated change in absolute bed roughness, is similar to the process of bed deformation in a sand bed river, and may be defined by relationships similar to those that exist between absolute bed roughness and particle characteristics under conditions of dynamic equilibrium on a deformed sand bed river.
- A fundamental approach towards the estimation of mean velocity under conditions of large scale roughness led to the development of a relatively simple and generally applicable equation. The application of this new equation to cobble and boulder bed rivers in the Western Cape, proved that it is able to provide a fairly accurate estimate of mean flow velocity under conditions of large scale roughness and can therefore be used for obtaining first order estimates of stage discharge relationships during the environmental flow assessment process.
- During low flows, the average hydraulic conditions within these reaches are inadequate for representing the diversity of local hydraulic conditions within the reach. Not only is each type of morphological unit associated with unique hydraulic characteristics, but, due to the effect of large scale roughness, the hydraulic conditions within each morphological unit also vary considerably.
- Each type of morphological unit displays significant variability in terms of its habitat diversity, with rapid and riffle morphological units characterized by more biotope classes and flow types than plane bed and pool morphological units.
- Biotope classes and flow types in cobble and boulder bed rivers may be classified in terms of their hydraulic characteristics. However, similar biotope classes and flow types display different hydraulic characteristics depending on the type of morphological unit in which they are situated. This implies that the hydraulic classification of habitat types in cobble and boulder bed rivers needs to accommodate the type of morphological unit within which they occur.

11.2 Recommendations

Based on the findings of this research programme, the following general recommendations can be made:

- Although all the models that have been developed as part of this research programme have been calibrated with extensive data sets, they have not, with the exception of the stage-discharge model, been verified with independent data sets. Before application of these models, it is therefore imperative that:

- the ability of the regime model to predict channel deformation is verified over a range of reach types and bed particle sizes. This may include laboratory studies.
- the sand scour model be verified in the field, possibly by means of controlled reservoir releases. The effects of absolute cobble size, non-uniform cobble size and steady state sediment transport conditions need to be investigated.
- the velocity distribution model be verified with additional field data and possibly further refined by introducing additional explanatory variables.

- As an additional verification exercise, it is recommended that the models which have been developed are used to determine the morphological and hydraulic characteristics of environmental flow components as specified in rivers where an environmental flow assessment has already been completed.
- It is recommended that the classification of habitat types in cobble and boulder bed rivers be expanded to accommodate the effect of morphological unit type. Furthermore a mathematical or statistical function, a "diversity index", should be developed, which will allow the quantification of habitat diversity per morphological unit, based on the assortment of biotope classes or flow types. This will allow the effect of a changing discharge regime on habitat characteristics to be anticipated.

12. BIBLIOGRAPHY

ABRAHAMS, A.D., LI, G. and ATKINSON, J.F. (1995). *Step-pool streams : Adjustment to maximum flow resistance*, Water Resources Res., Vol. 31, No. 10, pp 2593-2602.

ACKERS, P and CHARLTON, F.G (1970). *Meander geometry arising from varying flows*, J. of Hydrol., Vol. 11, 230 –252.

ACKERS P. and WHITE, W.R. (1973). *Sediment Transport: New Approach and Analysis*, J. Hydr. Eng., Proc. ASCE, Vol. 99, HY 11.

ANDREWS, E.D. (1979). *Scour and fill in a stream channel, East Fork River, Western Wyoming*, Water Resources Research., Vol 18, 1184-1192.

ANDREWS, E.D. (1980). *Effective and bankfull discharges of streams in the Yampa River Basin*, Colorado and Wyoming, J. of Hydrol., Vol 46, 311-330.

ANDREWS, E.D. (1982). *Bank stability and channel width adjustment, East Fork River, Wyoming*, Water Resources Res., Vol. 18, 1184-1192.

ANDREWS, E.D. (1983). *Entrainment of gravel from naturally sorted riverbed material*, Geol. Soc. Of Amer. Bull., Vol. 94, 1225-1231.

ARMITAGE, N.P. (2002). *A unit stream power model for the prediction of scour and deposition*, PhD Thesis, University of Stellenbosch

ARTHINGTON, A.H., BUNN.E., PUSEY, J., BLUHDORN, D.R., KING, J.M., DAY, J.A., THARME, R.E. and O'KEEFFE, J.H. (1992). Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems, in *Proceedings of an international seminar and workshop on water allocation for the environment*, Pigram, J.J. and Hooper, B.P. (eds), The Centre for Water Policy Research, University of New England, Armidale, Australia. 282 pp.

BAGNOLD, R.A. (1954). *Experiments on a gravity free dispersion of large solid spheres in a Newtonian fluid under shear*, Proc. Royal Soc., Ser. A, 225, 49-63.

BATHURST, J.C. (1978). *Flow resistance of large scale roughness*, J. Hydr. Div., ASCE, Vol. 104, No. HY12.

BATHURST, J.C., LI, R and SIMONS, D.B. (1981). *Resistance equation for large scale roughness*, J. Hydr. Div., ASCE, Vol. 107, No. HY12.

BATHURST, J.C. (1985). *Flow resistance estimation in mountain rivers*, J. Hydr. Eng.., ASCE, Vol. 111, No.4.

BECKETT, D.C., BINGHAM, C.R. and SANDERS, L.R. (1983). *Benthic macroinvertebrates of selected habitats of the lower Mississippi river*, J. Freshwater Ecology, 2(3), pp. 247 – 261.

BHOWMIK, N.G. and DEMISSIE, M (1982). *Bed material sorting in pools and riffles*, J. Hydr. Engineering, ASCE, Vol. 108, 1227-1231.

BOVEE, K.D. (1982). *A guide to stream habitat analysis using the Instream Flow Incremental Methodology*, Instream Flow Information Paper 12, FWS/OBS – 82/26, Co-operative Instream Flow Group, US Fish and Wildlife Service, Office of Biological Services. (As reference in Gordon *et al.*, 1992)

BOVEE, K.D. and COCHNAUER, T. (1977). *Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments : Fisheries*, Instream Flow Inf. Paper., 3, U.S. Fish and Wildlife Serv., Fort Collins, Colorado.

BOVEE, K.D. and MILHOUS, R.T. (1978). *Hydraulic simulation in instream flow studies : theory and techniques*, Instream Flow Information Paper 5, FWS/OBS – 78/33, Co-operative Instream Flow Services Group, Fort Collins, USA.

BRADLEY, J.N. and PETERKA, A.J. (1957). *The hydraulic design of stilling basins*, J. Hydr. Div., ASCE, Vol. 83, No. HY5.

BRAKENSIEK, D.L., OSBORNE, H.B. and RAWLS, W.J. (Co-ordinators) (1979). *Field Manual for Research in Agricultural Hydrology*, Agriculture Handbook 224, USDA.

BRAY, D.I. (1979). Estimating average velocity in gravel-bed rivers, J. Hydr. Div., ASCE, Vol. 105, No. HY9.

BRAY, D.I. (1982). Regime equations for gravel-bed rivers, in *Gravel-bed rivers*, Hey, R.D., Bathurst, J.C and Thorne, C.R. (eds.). John Wiley & Sons, Great Britain.

BROADHURST, L.J., HERITAGE, G.L., VAN NIEKERK, A.W., JAMES, C.S. and ROGERS, K.H. (1997). *Translating discharge into local hydraulic conditions on the Sabie River: An assessment of channel flow resistance*, WRC Report No. 474/2/97.

BROWN, C. and KING, J. M. (2000). *Environmental flow assessments : Concepts and methodologies*, World Bank Water Resources and Environmental Management Guideline Series, Guideline No. 6.

CARLING, P.A. (1991). *An appraisal of the velocity reversal hypothesis for stable pool-riffle sequences in the River Severn, England*, Earth Surface Processes and Landforms, Vol. 16, 19-31.

CHANG, H.H. and HILL, J.C. (1977). *Minimum stream power for rivers and deltas*, J. Hydr. Div., ASCE, Vol. 103, No. HY12.

CHANG, H.H. (1980). *Geometry of gravel streams*, J. Hydr. Div., ASCE, Vol. 106, No. HY9.

CHARLTON, F., BROWN, P.M. and BENSON, R.W (1978). *The hydraulic geometry of some gravel rivers in Britain*, Report No. IT 180, Hydraulic Research Station, Wallingford, England.

CHURCH, M. (1972). *Baffin Island sandurs: a study of Arctic fluvial processes*, Canadian Geol. Survey Bull., Vol. 216.

CHIN, A. (1999), *On the origin of step-pool sequences in mountain streams*, Geophysical Res. Letters, Vol. 26, No. 2, 231-234.

CHOW, V.T. (1959), *Open-channel hydraulics*, McGraw-Hill, USA.

COCHNAUER, T. (1976). Instream flow techniques for large rivers, in *Instream Flow Needs*, Orsborn, J.F. and Allman (eds.), C, Vol. II, pp. 387 – 399, American Fish. Soc.

COLLINGS, M. (1972). A methodology for determining instream flow requirements for fish, in *Proc. of Instream Flow Methodology Workshop*, pp. 72 –86, Washington Department of Ecology

DAVIES, T.H.R. and SUTHERLAND, A.J. (1983). Extremal hypothesis for river behaviour, Water Resources Res., Vol. 19, No. 1.

DAVIS, W.M. (1890). The rivers of Northern New Jersey, with note on the classification of rivers in general. National Geographic Magazine, 2, pp. 82-110.

DAVIS, J.A. and BARMUTA, L.A. (1989). *An ecologically useful classification of mean and near-bed flows in stream and rivers*, Freshwater Biology, pp. 271 – 282.

DINGMAN, S.L. (1989). Probability distribution of velocity in natural cross sections, Water Resources Res. 25 (3), pp. 509-518.

DURY, G.H. (1954). *Contribution to a general theory of meandering valleys*, Am. J. Sci.., Vol 252.

DURY, G.H. (1959). *Analysis of regional flood frequency on the Nene and the Great Ouse*, Geog. J. Vol. 125, 223-229.

DURY, G.H. (1961). *Bankfull discharge – an example of its statistical relationships*. Bull. Int. Assoc. Scientific Hydrology Vie Annee, No. 3, 48.

ENGELUND, F. (1970). *Instability of Erodible Beds*, Journal of Fluid Mechanics, Vol. 42, Part 2.

FERRO, V. and GIORDANO, G. (1991). *Experimental study of flow resistance in gravel-bed rivers*, J. Hydr. Eng.., ASCE, Vol. 117, No.10.

GLOVER, R.E. and FLOREY, Q.L. (1951). *Stable channel profiles*, U.S. Bureau of Reclamation Hyd. Lab. Report Hyd-325

GORDON, N.C., McMAHON, T.A. and FINLAYSON, B.L. (1992). *Stream hydrology – An Introduction for Ecologists*, John Wiley and Sons, England.

GORE, J.A. (ed) (1985). *The Restoration of Rivers and Streams*, Butterworths, Boston, Massachusetts.

GRAF, W.H. (1971). *Hydraulics of Sediment Transport*, McGraw-Hill, New York.

GRAF, W.H. (1984). *Hydraulics of Sediment Transport*, Water Resources Publications.

GRANT, G.E., SWANSON, F.J. and WOLMAN, M.G. (1990). *Pattern and origin of stepped bed morphology in high gradient streams*, Western cascades, Oregon. Geological Society of America Bulletin, Vol. 102, pp. 305-352.

GRASS, A.J. (1970), *The initial instability of fine sand*, J. Hydr. Div., Proc. ASCE, Vol. 96, No. HY3.

GRIFFITHS, G.A. (1981) Flow resistance in coarse gravel bed rivers, in *Gravel-bed rivers*, Hey, R.D., Bathurst, J.C and Thorne, C.R. (eds.), John Wiley & Sons, Great Britain.

HARRISON, A.D. and ELSWORTH, J.F. (1959). *Hydrobiological studies on the Great Berg River, Western Cape Province*, Transactions of the Royal Society of South Africa, 2.

HARVEY, A.M. (1969). *Channel capacity and the adjustment of streams to hydrologic regime*, J. Hydrology, Vol 8, pp. 82-98

HEY, R.D. (1979). *Flow resistance in gravel bed rivers*, J. Hydr. Div., ASCE, Vol. 105, No. HY4.

HEY, R.D. (1982). Design equations for mobile gravel-bed rivers, in *Gravel-bed rivers*, Hey, R.D., Bathurst, J.C and Thorne, C.R. (eds.), John Wiley & Sons, Great Britain.

HEY, R.D. and THORNE, C.R. (1983). *Hydraulic geometry of mobile gravel-bed rivers*, Proc. Second Int. Symp. On River Sedimentation, Nanjing, China, Vol. 1, Paper C11.

HEY, R.D. and THORNE, C.R. (1986). *Stable channels with mobile gravel beds*, ASCE J. Hydr. Eng., Vol. 112, No. 8

HEY, R.D., BATHURST, J.C. and THORNE, C.R. (1982). *Gravel-bed rivers*, John Wiley & Sons, Great Britain.

HIRSCH, P.J. and ABRAHAMS, A.D. (1981). *The properties of bed sediments in pools and riffles*, J. Sedim. Petrol., Vol. 51, 757-760.

HJULSTRöM, F. (1939). *Transportation of detritus by moving water*, in Recent Marine Sediments, A symposium, Trask, P.D. (ed), pp 5-31, Amer. Ass. of Petroleum Geologists, Tulsa.

HUGUES, R.M., WHITTLER, T.R., ROHM, C.M., LARSEN, D.P. (1990). *A regional framework for establishing recovery criteria*. Environmental Management 14, pp. 673 – 683.

JARRET, R. D. (1984). *Hydraulics of high gradient streams*, ASCE J. Hydr. Eng. 110, pp 1519-1539

JOWETT, I.G. (1993). *A method for objectively identifying pool, run and riffle habitats from physical measurements*. New Zealand Journal of Marine and Freshwater Research, Vol. 27, pp 241 – 248.

KAY, M. (1998). *Practical Hydraulics*, E & FN, Great Britain

KELLER, E.A. (1971). *Arial sorting of bed load material, the hypothesis of velocity reversal*, Geol. Soc. of America Bulletin, Vol. 82, pp. 753-756.

KELLER, E.A. and MELORN, W.N. (1978). *Rhythmic spacing and origin of pools and riffles*, Geol. Soc. of America Bulletin, Vol. 89, pp. 723-730.

KELLER, E.A. and MELHORN, W.N. (1974). *Form and fluvial processes in alluvial stream channels*, Purdue Univ. Water Resources Research Center Tech. Report No. 47, 124 pp.

KELLERHALS, R (1967). *Stable channels with gravel paved beds*, ASCE Jnl. Of Waterways and Harbors Div. , Vol. 93, No. WW1, 63-83.

KELLERHALS, R. and CHURCH, M. (1989). The morphology of large rivers : characterization and management, in *Proceedings of the International Large River Symposium*, Dodge, D.P. (ed), Can. Spec. Publ. Fish Aquatic Sci, 106, pp 31-48.

KENNEDY, J.F. (1961). *Stationary waves and antidunes in alluvial channels*, Report No. KHR2, California Institute of Technology, Pasadena.

KEULEGAN, G.H. (1938). *Laws of turbulent flow in open channel*, J. of Research, Paper RP1151, US Natural Bureau Standards, Vol 21, 707-741.

KING, J.M. (2001). Personal communication. Freshwater Research Unit, University of Cape Town.

KING, J.M. and SCHAEL, D.M. (In press). *Testing the ecological relevance of a spatially-nested geomorphological hierarchy for river management*, Report to the WRC on the project "Linking abiotic and biotic data on South African rivers"

KING, J.M. and THARME, R.E. (1994). *Assessment of the instream flow incremental methodology, and initial development of alternative instream flow methodologies for South Africa*, WRC Report No. 295/1/94.

KING, J.M. and LOUW, D (1998). *Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology*, Aquatic Ecosystem Health and Management 1, pp. 109 – 124.

KNIGHTON, A.D. (1984). *Fluvial forms and processes*, Edward Arnold, Maryland, USA.

KONDOLF, G.M. and WILCOCK, P.R. (1996), *The flushing flow problem : Defining and evaluating objectives*, Water Resources Research, Vol. 32.

LAMOUROUX, N., SOUCHON, Y. and HEROUIN, E. (1995). *Predicting velocity frequency distributions in stream reaches*, Water Resources Research, Vol. 31, No.9.

LANE, E.W. and KALINSKE, A.A. (1939). *The relation of suspended load to bed material in rivers*, Trans. Am. Geol. Union, Vol. 20.

LANE, E.W., LIN, P.N. and LIU, H.K. (1959). *The most efficient stable channel for comparatively clean water in non-cohesive material*, Report CER59HKL5, Colorado State University, Fort Collins.

LE GRANGE, A.D. (1994). *Techniques for predicting the deformation and hydraulic resistance of sand-bed flow channels*, PhD Thesis, University of Stellenbosch.

LEOPOLD, L.B. and WOLMAN (1957). *River patterns: Braided, meandering and straight*, US Geol. Survey Prof. Paper. 282-B, 56.

LEOPOLD, L.B. (1992). Sediment size that determines channel morphology, in *Dynamics of gravel bed rivers*, Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. (eds), Wiley, New York.

LEOPOLD, L.B. and LANGBEIN, W.B. (1962). *The concept of entropy in landscape evolution*, U.S. Geol. Surv. Prof. Paper 500A.

LEOPOLD, L.D., WOLMAN, M.G. and MILLER, J.P. (1964). *Fluvial Processes in Geomorphology*. WH Freeman, San Fransisco.

LI, R.M., SIMONS, D.B. and STEVENS, M.A. (1976). *Morphology of cobble streams in small watersheds*, J. Hydr. Div., ASCE, Vol. 102, HY8, pp 1101 – 1117.

LIGON, F.K., DIETRICH, W.E. and THRUSH, W.J. (1995), *Downstream ecological effects of dams, a geomorphic perspective*, Bioscience, 45(3).

LIMERINOS, J.T. (1970). *Determination of the Manning coefficient from measured bed roughness in natural channels*. US Geol. Survey Water Supply Paper1898-B, USGS, Washington DC.

LISLE, T.E. (1979). *A sorting mechanism for a riffle pool sequence: Summary*, Bull. Geol. Soc. Am., Vol. 90, 616-617.

LIU, H.K. (1957). *Mechanics of sediment-ripple formation*, Proc. Am. Soc. Civil Engrs., Vol. 83, No. HY2.

MASSEY, B.S. (1989). *Mechanics of fluids*, Chapman & Hall, Great Britain.

MILHOUS, R.T., UPDIKE, M.A. and SCHNEIDER, D.M. (1989). *Physical habitat simulation system reference manual –version II*. Instream Flow Information Paper 26, U.S. Fish and Wildlife Services Biol. Report 89(16), Fort Collins, U.S.A.

MILNE, J.A. (1982). *Bed material size and the riffle pool sequence*. Sedimentology, Vol. 29, 267-278.

MONTGOMERY, D.R. and BUFFINGTON, J.M. (1993). *Channel classification, prediction of channel response and assessment of channel condition*. Draft report prepared for the SHAMWU committee of the Washington State Timber/Fish/Wildlife Agreement.

MOSLEY, M.P. (1982). *A procedure for characterizing river channels*. Water and Soil miscellaneous publication 32, Ministry of Works and Development, Wellington.

NESTLER, J.M., MILHOUS, R.T. and LAYZER, J.B. (1989). Instream habitat modelling techniques, in *Alternatives in Regulated River Management*, Gore, J.A. and Petts, G.E. (eds), CRC Press, Florida, pp. 295-315.

NEWSON, M., THORNE, C.R., HEY, R. (1998). *Applied fluvial geomorphology*, John Wiley and Sons, Chichester.

O'NEILL, M.P. and ABRAHAMS, A.D. (1984). *Objective identification of pools and riffles*. Water Resources Res. 20, pp 921 – 926.

ORTH, D.J. and MAUGHAN, O.E. (1982). *Evaluation of the incremental methodology for recommending instream flow for fishes*, Trans. Am. Fish. Soc., 3, pp. 413-445.

PARKER, G. (1975). *Sediment inertia as cause of river antidunes*, ASCE J. Hydr. Div., Vol. 101 (HY2), 211-221.

PARKER, G. (1979). *Hydraulic geometry of active gravel rivers*, J. Hydr. Div., ASCE, Vol. 105, No. HY9, pp. 1185-1201.

PETTS, G.E. and FOSTER, I (1985). *Rivers and Landscape*, Edward Arnold, London.

PICKUP, G. (1984). Geomorphology of tropical rivers, in *Channel Process-Water, Sediment catchment controls*, Schick, A.P. (ed), Catena Supplement 5, W Germany, pp 1-41.

PRANDTL, L. (1926). *"Uber die ausgebildeteTurbulenz."* Z. Angew. Math. Mech. Bd. 5, 136-139.

PYLE, R. and NOVAK, P. (1981). *Coefficient of friction in conduits with large roughness*, J. Hydr. Res. 19, No. 2

REISER, D.W., RAMEY, M.P., WESCHE, T.A. (1989). Flushing flows, in *Alternatives in Regulated River Management*, Gore, J.A. and Petts, G.E. (ed.), CRC Press, Boca Raton, Fla.

REYNOLDS, A.J. (1965). *Waves on the erodible bed of an open channel*, J. Fluid Mech. Vol. 22, 114-133.

RICHARDS, K.S. (1976). *The morphology of riffle-pool sequences*, Earth Surf. Proc. 1, pp 71 – 88.

RICHARDS, K.S. (ed) (1987). *River channels : Environment and Process*, Oxford, Blackwell.

RICHARDS, K.S. (1982). *Rivers. Form and Process in alluvial channels*, Methuen, London.

RICHTER, B.D., BAUMGARTNER, J.V., WIGINGTON, R. and BRAUN, D.P. (1997). *How much water does a river need?*, Freshwater Biology, 37, pp. 231 – 249.

ROGERS, K.H., PULLEN, R.A., O'KEEFFE, J.H., MOON, B.P. (1992). *An integrated programme for research on the Kruger National Park's rivers*, Unpublished report

ROOSEBOOM, A. (1974), *Open channel fluid mechanics*, Technical Report No. 62, Department of Water Affairs, Pretoria, SA.

ROOSEBOOM, A. (1992). *Sediment transport in rivers and reservoirs – a South African perspective*, WRC Report No. 297/1/92.

ROOSEBOOM, A (1994), *Open channel flow*, University of Stellenbosch post-graduate lecture notes.

ROOSEBOOM, A. (1998), *The cinderella of hydraulics – the law of conservation of power*. Proc. 3rd International conference on Hydroscience and Engineering. Cottbus, Germany.

ROOSEBOOM, A. and LE GRANGE, A. (1994), *Equilibrium scour in rivers with sandbeds*. 2nd Int. conference on River Flood Hydraulics, York, England.

ROOSEBOOM, A. and LE GRANGE, A. (2000), *The hydraulic resistance of sand streambeds under steady flow conditions*. Journal of Hydraulic Research, Vol. 38, No. 1.

ROSGEN, D.L. (1994). *Classification of natural rivers*. Catena, Vol. 22.

ROUSE, H. (1937). *Modern Conceptions of Mechanics of Fluid Turbulence*, Trans. ASCE, Vol. 102

ROWNTREE, K.M. (ed) (1996). *The hydraulics of physical biotopes : terminology, inventory and calibration,* Water Research Commission Report KV84/96, Water research Commisssion, Pretoria, South Africa.

ROWNTREE, K.M. and WADESON, R.A. (1996). *Translating channel morphology into hydraulic habitat : application of the hydraulic biotope concept to an assessment of discharge related habitat changes*, Proceedings 2nd IAHR International Symposium on Hydraulics and Habitats, Quebec City, June 11 –14.

ROWNTREE, K.M. and WADESON, R.A. (1999). *A hierarchical geomorphological model for the classification of selected South African rivers*, WRC Report No. 497/1/99.

SCHEUERLEIN, H. (1999). Morphological dynamics of step-pool systems in mountain streams and their importance for riparian ecosystems, in *River Sedimentation*, Jayawardena, Lee and Wang (eds.), Balkema, Rotterdam.

SCHLICHTING, H. (1979). *Boundary layer theory*, McGraw-Hill, New York.

SCHUMM, S.A. (1977). *Fluvial Systems*, John Wiley, New York.

SELBY, M.J. (1985). *Earth's changing surface : an introduction to geomorphology*, Oxford University Press, Oxford.

SHAW, J. and KELLERHALS, R. (1977). *Paleohydraulic interpretation of antidune bedforms with application to antidunes in gravel*, J. of Sed. Petrology, Vol. 47, No. 1, pp. 257-266.

SHIELDS, N.D. (1936). Anwendung der ahnlickeit Mechanik und der turbulenzforschung auf die Geschiebelerwegung, *Mitt. Preoss Versuchanstalt fur Wasserbau und Schiffbau.*

SIDLE, R.C. (1988). *Bed load transport regime of a small forest stream*, Water Resources Res., Vol. 24, 207-218.

SIMONS, D.B., LI, R. (1989). *Flow resistance in cobble and boulder bed rivers*, J. Hydr. Div., ASCE, Vol. 105, HY5.

SONG, C.C.S. and YANG, C.T. (1982). *Minimum stream power : theory*, J. Hydr. Div., ASCE, Vol. 106, HY9.

STATZNER, B. and HIGLER, B. (1986). *Stream hydraulics as a major determinant of benthic invertebrate zonation patterns*, Freshwater Biology 16, pp. 127 - 139.

TENNANT, D.L. (1976). *Instream flow regimens for fish, wildlife, recreation and related environmental resources*, Fisheries, Vol. 1, No. 4.

THARME, R.E. (1996). *Review of international methodologies for the quantification of the instream flow requirements of rivers*, Department of Water Affairs and Forestry, Pretoria, South Africa.

THOMPSON, S.M. and CAMPBELL, P.L. (1979). *Hydraulics of a large channel paved with boulders*, Journal of Hydr. Research, Vol 17.

THORNE, C.R. and ZEVENBERGEN, L.W. (1985). *Estimating mean velocity in mountain rivers*, Jnl. Hydr. Engineering, Vol. 111, No. 4.

TUNBRIDGE, B.R. (1988). *Environmental flows and fish populations of waters in the South-Western Region of Victoria,* Tech. Report Series No. 65, Arthur Rylah Inst. for Env. Res. , Dept. Cons. Forests and Lands, Victoria, Australia. (As reference in Gordon *et al.*, 1992)

VALENTINE, H.R. (1967). *Water in the service of man*, Pelican.

VAN NIEKERK, A.W., HERITAGE, G.L. and MOON, B.P. (1995). *River classification for management : the geomorphology of the Sabie River in the Eastern Transvaal*, South African Geographical Journal, 77(2), pp. 68-76.

VAN RIJN, L.C. (1993). *Principles of sediment transport in rivers, estuaries and coastal seas*, Aqua Publications, The Netherlands.

WADESON, R.A. (1996). *The development of the hydraulic biotope concept within a hierarchical geomorphological model*, PhD Thesis, Rhodes University, Grahamstown, South Africa

WADESON, R.A. and ROWNTREE, K.M. (1998). *Application of the hydraulic biotope concept to the classification of instream habitats*, Aquatic Ecosystem Health and Management 1, pp. 143 – 157.

WADESON, R.A. and ROWNTREE, K.M. (1999). *A hierarchical geomorphological model for the classification of selected South African rivers*. WRC Report No. 497/1/99

WATERS, B.F. (1976). A methodology for evaluating the effects of different streamflows on salmonid habitat, in *Instream Flow Needs*, Orsborn, J.F. and Allman, C.H. (eds), Am. Fisheries Soc. Bethesda.

WHITE, R.G. (1976). A methodology for recommending stream resource maintenance flows for large rivers, in *Proc. of the Symp. and Spec. Conf. On Instream Flow Needs*, Orsborn, J.F. and Allman (eds.), Vol II, pp. 367 – 386, Amer. Fish. Soc., Bethesda, Maryland. (As reference in Gordon *et al.*, 1992)

WHITE, W.R., BETTESS, R., PARIS, E. (1982). Analytical approach to river regime, J. Hydr. Div., ASCE, Vol. 108, HY10.

WHITTAKER, J.G. and JAEGGI, M.N.R. (1982), *Origin of step-pool systems in mountain streams*, J. Hydr. Div., ASCE, Vol. 108, HY6.

WILCOCK, P.R., KONDOLF, G.M., MATTHEWS, W.V.G. and BARTA, A.F. (1996), *Specification of sediment maintenance flows for a large gravel-bed river*, Water Resources Research, Vol. 32, No. 9.

WOODYER, K.D. (1968), *Bankfull frequency in rivers*, J. of Hydrol. Vol. 6, 114-142.

WOLMAN, M.G. (1954). *A method of sampling coarse river-bed material*, Trans. American Geophysical Union, Vol. 35 No. 6

WOLMAN, M.G. (1955). *The natural channel of Brandywine creek, Pennsylvania*. U.S. Geological Surv. Proff. Paper 271, USGS Washington.

YALIN, M.S. (1992). *River Mechanics*, Pergamon Press, Great Britain

YANG, C.T. (1971). *Formation of riffles and pools*, Water Resources Res. 7, pp 1567 – 1574.

YANG, C.T. (1973), *Incipient motion and sediment transport*, J. Hydr. Div., Proc. ASCE, Vol.99, No. HY10.

YANG, C.T. (1976). Minimum unit stream power and fluvial hydraulics. J. Hydr. Div., ASCE, Vol. 102, HY7.

YANG, C.T. (1984). *Unit stream power equation for gravel*, J. Hydr. Div., ASCE, Vol. 110, HY12.

APPENDIX A: The hydraulic characteristics of winter rainfall region monitoring sites used in the WRC Project on Biotic Abiotic Links

WATER RESEARCH COMMISSION

HYDRAULIC DATA ANALYSIS : BIOTIC – ABIOTIC LINKS PROJECT

October 1999

V Jonker

1. INTRODUCTION

The current WRC Project on Biotic – Abiotic Links in South African rivers by the FRU at UCT, aims to determine the character of the available or potentially available abiotic and biotic data on South African rivers and the links between such data sets ; and then to explore ways in which to integrate such data sets so that they are used to their best potential for the purposes of research and sustainable management of rivers.

Another WRC Project currently underway at the University of Stellenbosch, aims to identify hydraulic relationships in winter rainfall rivers for determining ecological flow requirements in these rivers. As part of the project proposal, it was indicated that the hydraulic database established by the FRU during the Biotic – Abiotic Links project, will be evaluated to determine the extent of hydraulic relationships in these winter rainfall region sites and their relevance to ecological habitats.

2. DATA

During the data collection phase of the Biotic – Abiotic Links project, physical habitats were mapped and invertebrate samples and supporting physical and chemical data collected in 28 winter rainfall rivers of which about 19 are pristine.

The hydraulic data per site, or river, included one channel cross section utilising a tape and a marked pole, the local slope, a discharge as well as local hydraulic conditions at each invertebrate sample collection point. For each invertebrate sample collected, about twelve per site, the following data on local hydraulics were collected at two to four points within the sample area :

- The **flow type** (based on the appearance of the water surface)

- The dominant and sub-dominant **substratum** types
- The degree of **embeddedness** of coarse substratum particles in fines
- The **flow velocity** at near-bed and 0,6 of total depth (In deep water additional measurements were taken at 0,2 and 0,8 of total depth)
- The **flow depth**

Bed heterogeneity was also measured.

3. DATA ANALYSIS

The analysis of the hydraulic data focused on the hydraulic data collected within each invertebrate sample area, specifically the dominant substratum, the flow type, the flow depth and the average velocity. Data from all 28 rivers, both pristine and disturbed, were included. The cross sectional data was not incorporated into the analysis, as it could not be linked to specific hydraulic data available in the database. Furthermore, data on the channel slope was also not incorporated into the analysis. However, channel slope was considered indirectly by distinguishing between mountain and foothill stream reaches as indicated in the database.

The analysis is based mainly on the concept of **hydraulic biotopes**. A hydraulic biotope is defined as a "spatially distinct instream flow environment characterised by specific hydraulic attributes that provide the abiotic environment in which species assemblages or communities live". Hydraulic biotopes are recognised on the basis of surface flow type and substrate class, where flow type describes the appearance of the water surface.

It was therefore possible to assign each of the hydraulic data sample points to a specific biotope class based on the combination of flow type and substrate (This was done in accordance with the hydraulic biotope matrix (Rowntree, 1996)). Furthermore, from the available measurements of flow depth and velocity, hydraulic indices were calculated , i.e. Froude and Reynolds number and the velocity/depth ratio.

Table 1 provides information on the number of data points per hydraulic biotope class which were used in the analyses. A distinction is made between mountain and foothill reaches.

BIOTOPE	FOOTHILL	MOUNTAIN	TOTAL
Backwater	4	0	4
Cascade	29	104	133
Chute	5	31	36
Glide	77	105	182
Pool	54	55	109
Rapid	40	36	76
Riffle	132	156	288
Run	137	165	302

Table 1 : Number of data points used in analyses

Three types of analyses were performed, viz.

- The hydraulic characteristics of hydraulic biotope classes
- Assessment of habitat diversity
- Velocity frequency distribution

3.1 The hydraulic characteristics of hydraulic biotope classes

The probability distribution of three hydraulic indices (Froude No., Reynolds No. and the velocity/depth ratio) across different hydraulic biotopes was investigated. In addition, it was investigated whether there is a significant difference in the probability distribution of hydraulic indices for similar biotope classes in mountain and foothill reaches.

Figures 1 a to c display the probability distribution curves for Froude No., Reynolds No. and the velocity/depth ratio respectively.

All three graphs indicate that there is a distinct probability distribution pattern associated with each biotope class. The higher velocity / steep slope biotopes show greater variation in the values of the hydraulic indices with more values in the higher ranges. It is also evident that the flow range of the majority of biotopes is dominated by the subcritical range (Fig. 1 a). Only the chute, cascade and rapid biotopes have a notable percentage of flows in the supercritical range.

Figures 2, 3 and 4 (a to g) show the variation in the probability distribution for similar biotope classes in mountain and foothill reaches. Although no definite patterns are evident, it does appear that in general, the probability distribution curves for foothill reaches plot below those for mountain reaches up to about the 80th or 90th percentile. This is contrary to expectations as one would associate higher slopes in mountain reaches with higher veloicities and Froude numbers as well as Reynolds numbers. It may, however, be attributed to inconsistencies in the classification of mountain and foothill reaches.

3.2 Assessment of habitat diversity

Figures 5 a and b display the habitat diversity in the mountain reaches as opposed to the foothill reaches based on all the data collected. The pie charts give a good visual indication of both the diversity of hydraulic biotopes and the dominant biotope. In both the mountain and foothill reaches, the dominant biotopes are runs and riffles. Cognisance, however, should be taken of the fact that the hydraulic data was not collected at evenly spaced intervals over the river reach. The data may therefore not be representative of the entire reach under consideration.

Figures 6 a to f indicate the habitat diversity associated with each substrate type across mountain and foothill reaches. It is interesting to note the dominant biotope class associated with each substrate and also the variation in the dominant biotope class over each substrate in mountain and fooothill reaches.

3.3 Velocity frequency distribution

Figures 7 a to g display the frequency distribution of point velocities across different biotope classes, as expressed by the relative velocity V/V_{avg}. V_{avg} represents the average point velocity per hydraulic biotope per site and not an average cross section velocity.

Based on the graphical interpretation, it seems that overall, the data displays a positive skewness and might fit the log-normal distribution or logP III distribution. The standard deviation varies between 0,5 and 0,7 (except for the glide biotope) as displayed in the following table :

BIOTOPE	STANDARD DEVIATION
Cascade	0.579
Chute	0.571
Glide	1.507
Pool	0.580
Rapid	0.648
Riffle	0.688
Run	0.682

Table 2 : Standard deviation of velocity frequency distributions

4. CONCLUSION

Based on the results of the data analyses, the following conclusions can be drawn :

- Hydraulic biotope classes, as defined in terms of a combination of substrate and flow type, are characterised by unique hydraulic attributes. This appears to be generally consistent across the spatial scale of mountain and foothill reaches.
- Habitat diversity over similar substrate classes, display significant differences between mountain and foothill reaches. This can be ascribed to the different flow types over these substrates in mountain and foothill reaches and again confirms the biotope concept.
- A graphical interpretation of the frequency distribution of point velocities did not reveal much. However, a statistical analysis might lead to more definite distinctions between the different biotopes. A cross sectional average velocity as opposed to the average point velocity used in this analysis, might also prove more fruitful.

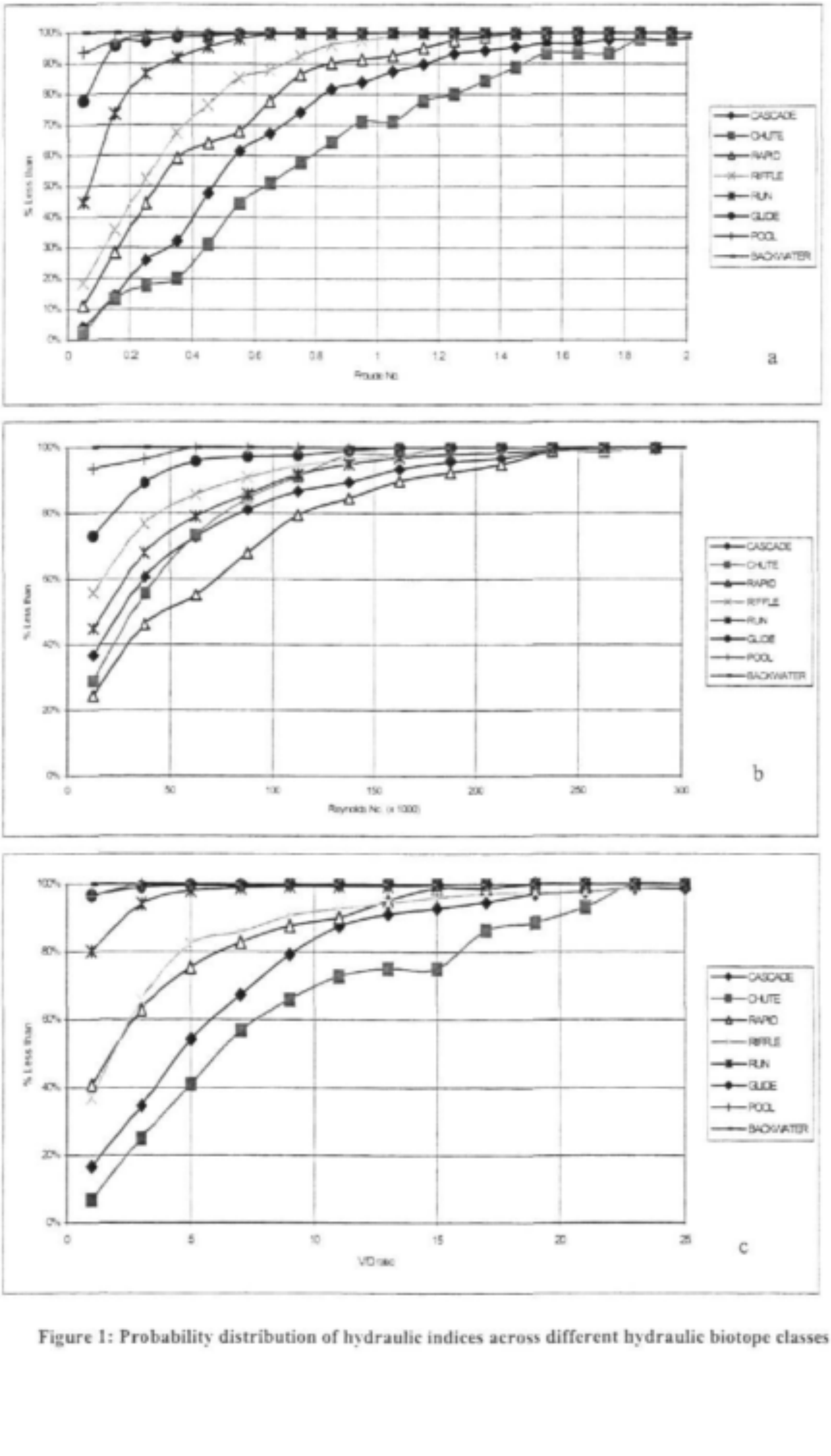


Figure 1: Probability distribution of hydraulic indices across different hydraulic biotope classes

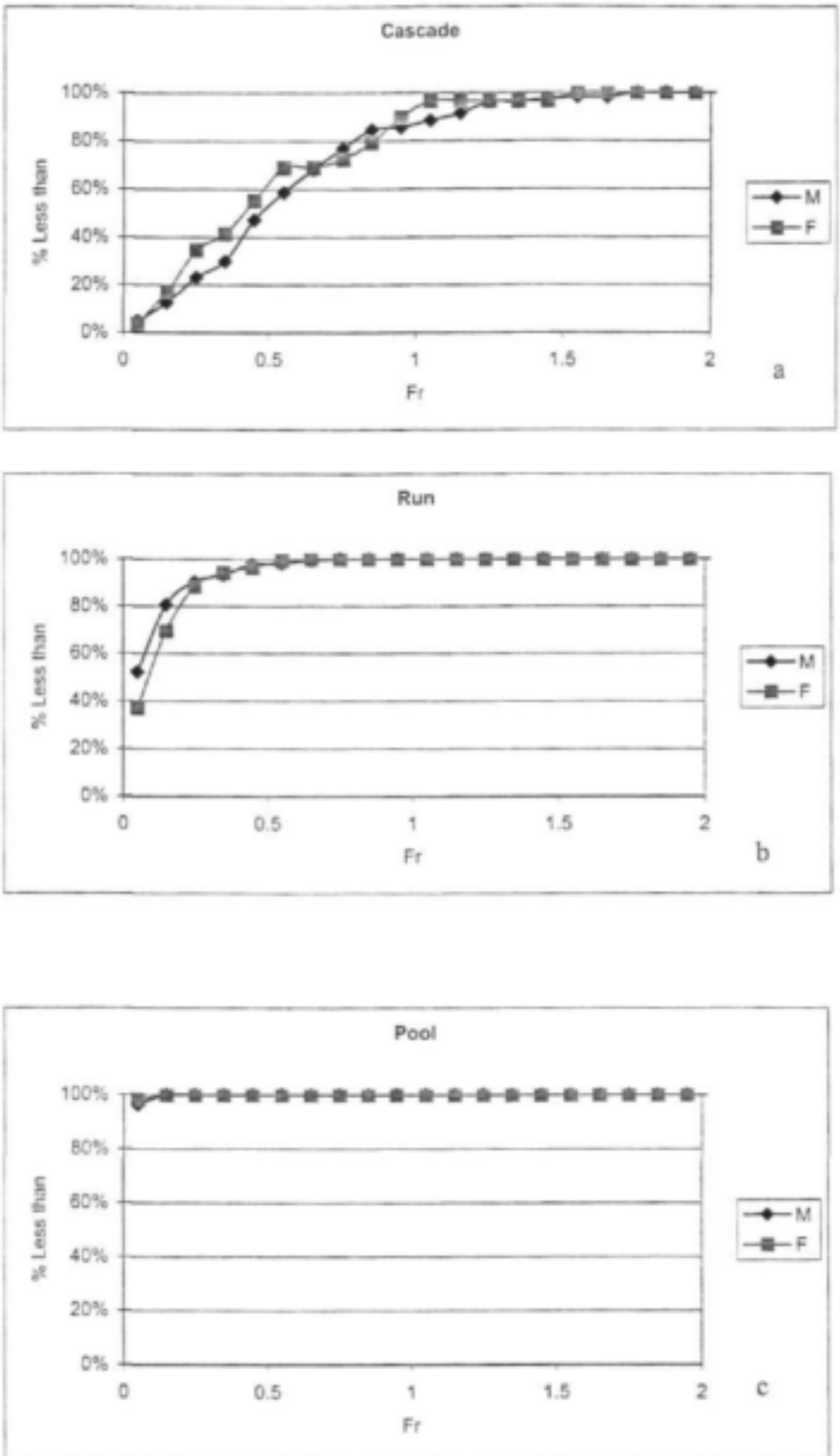
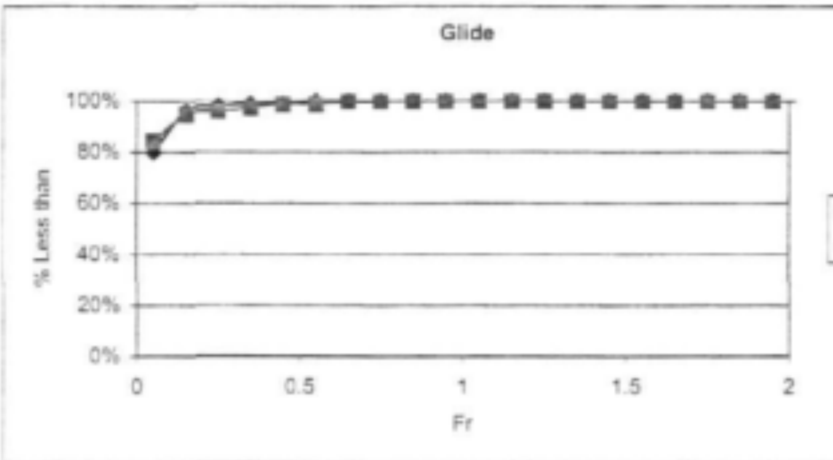
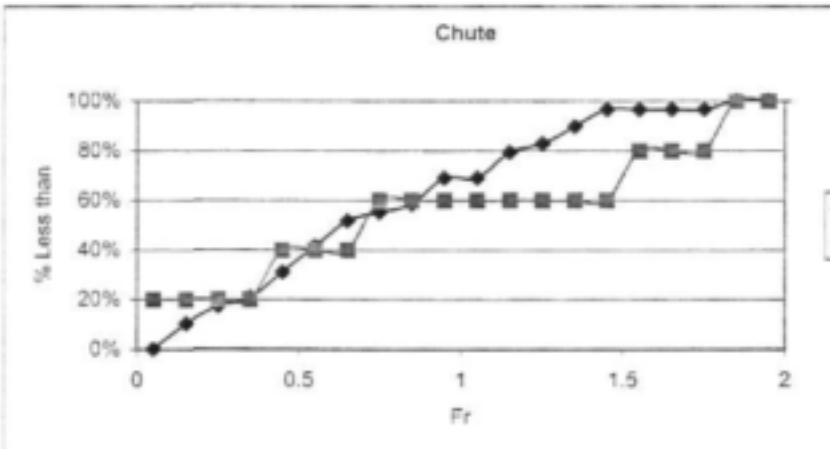


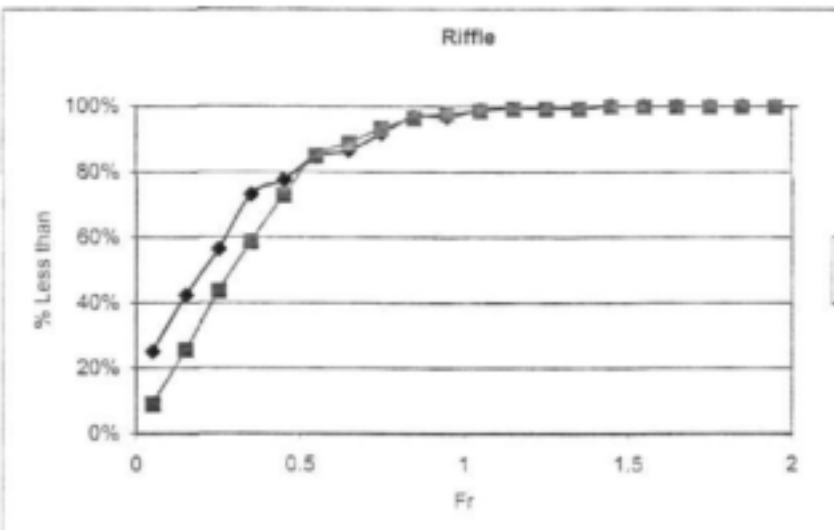
Figure 2: Froude number probability distribution in hydraulic biotope classes



d



e



f

Figure 2: Froude number probability distribution in hydraulic biotope classes (cont.)

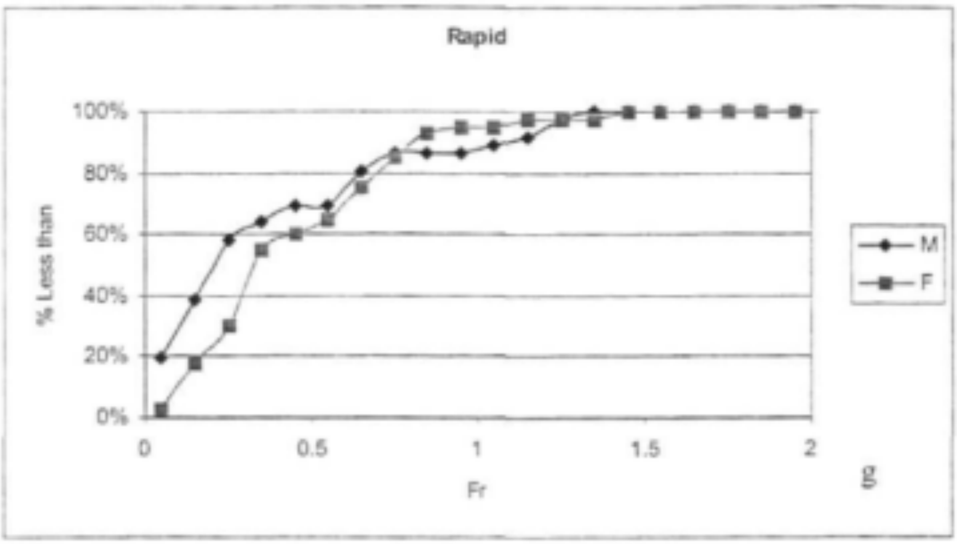


Figure 2: Froude number probability distribution in hydraulic biotope classes (cont.)

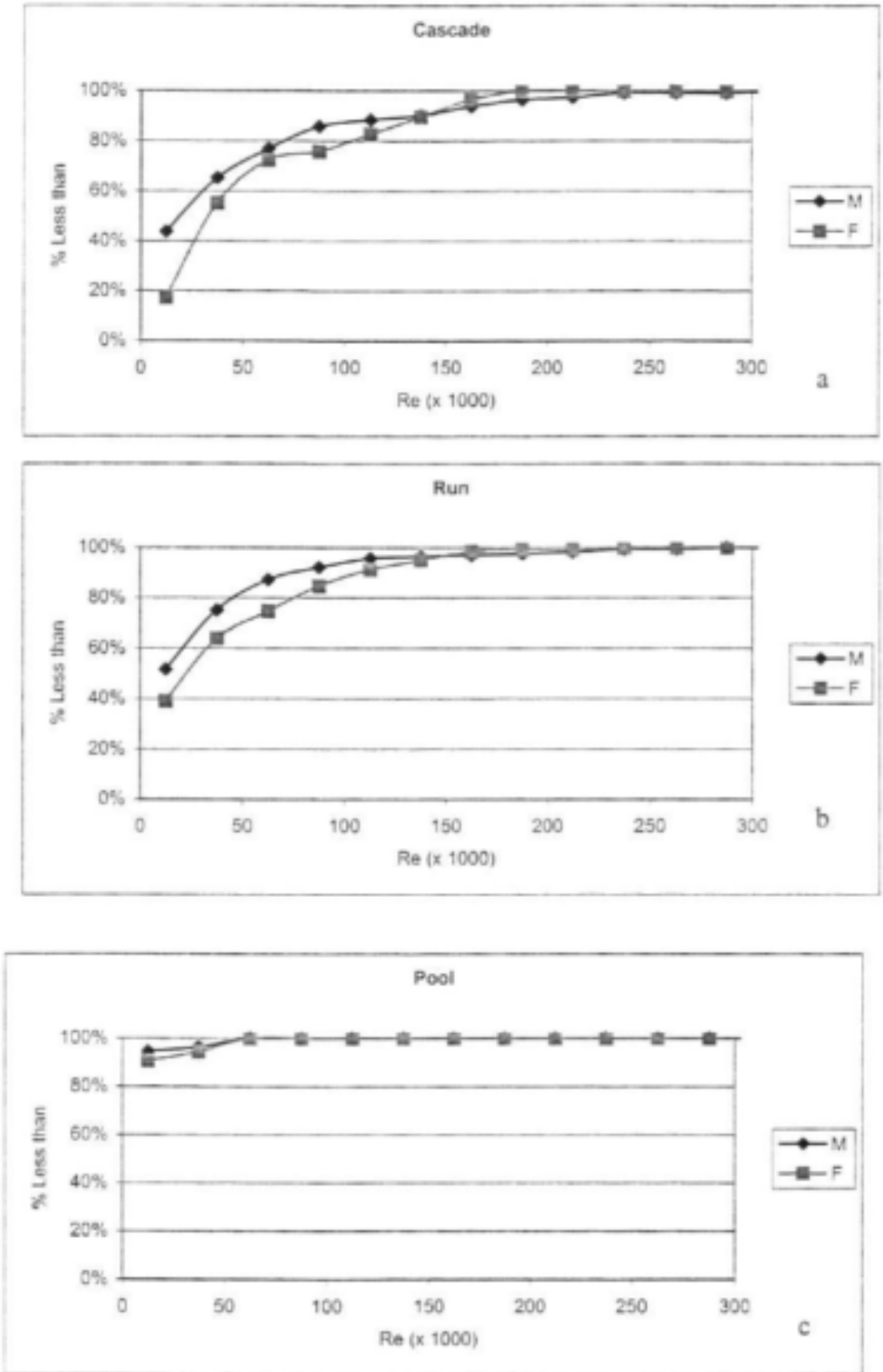
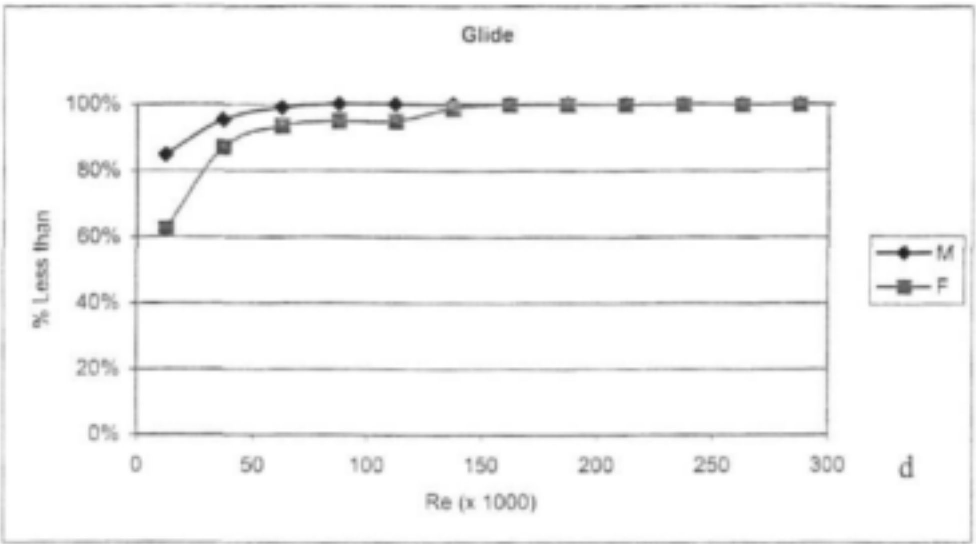
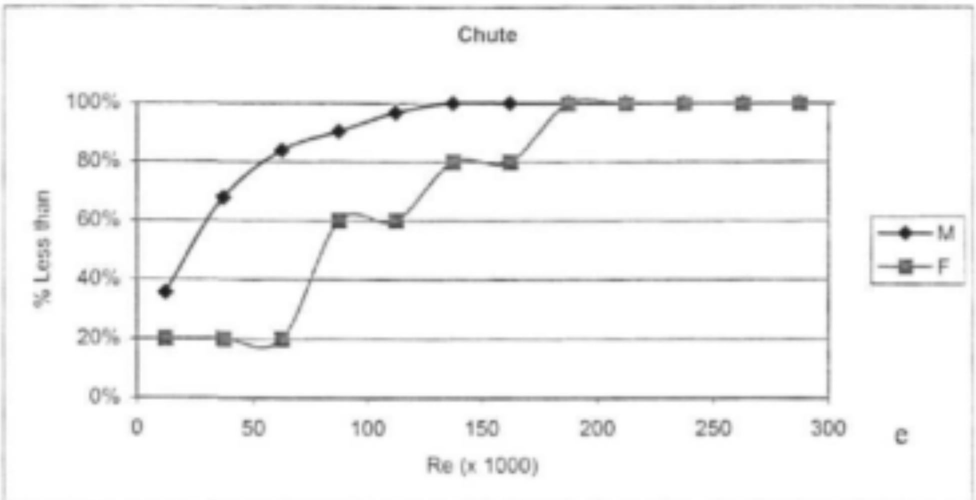


Figure 3: Reynolds number probability distribution in hydraulic biotope classes





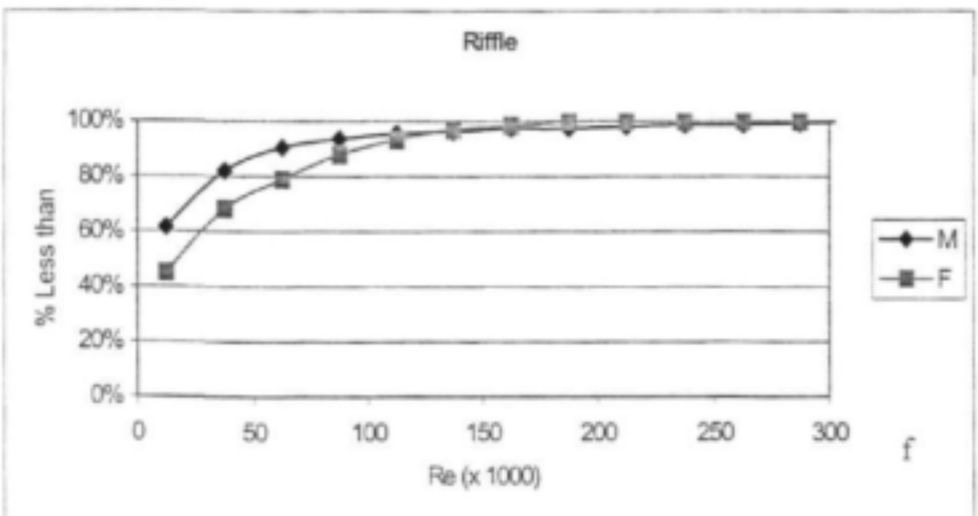


Figure 3: Reynolds number probability distribution in hydraulic biotope classes (cont.)

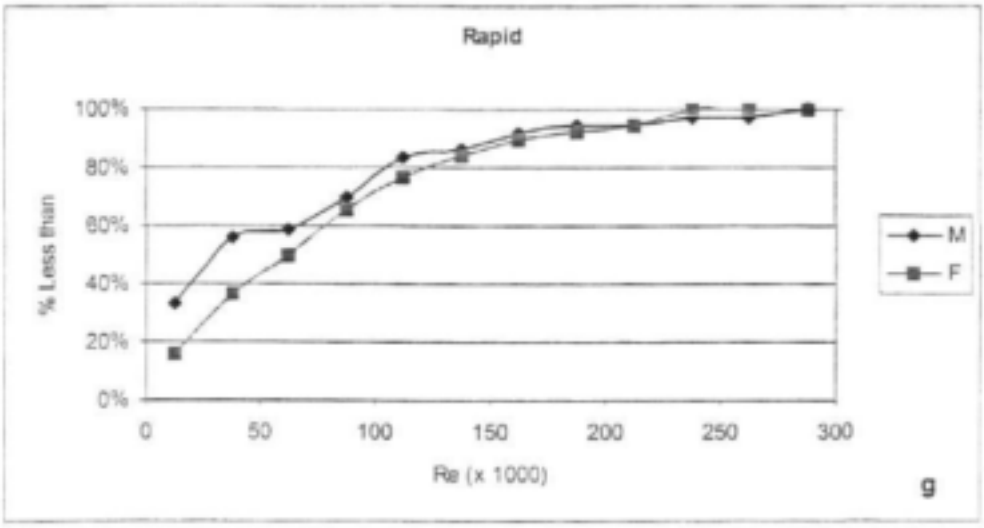


Figure 3: Reynolds number probability distribution in hydraulic biotope classes (cont.)

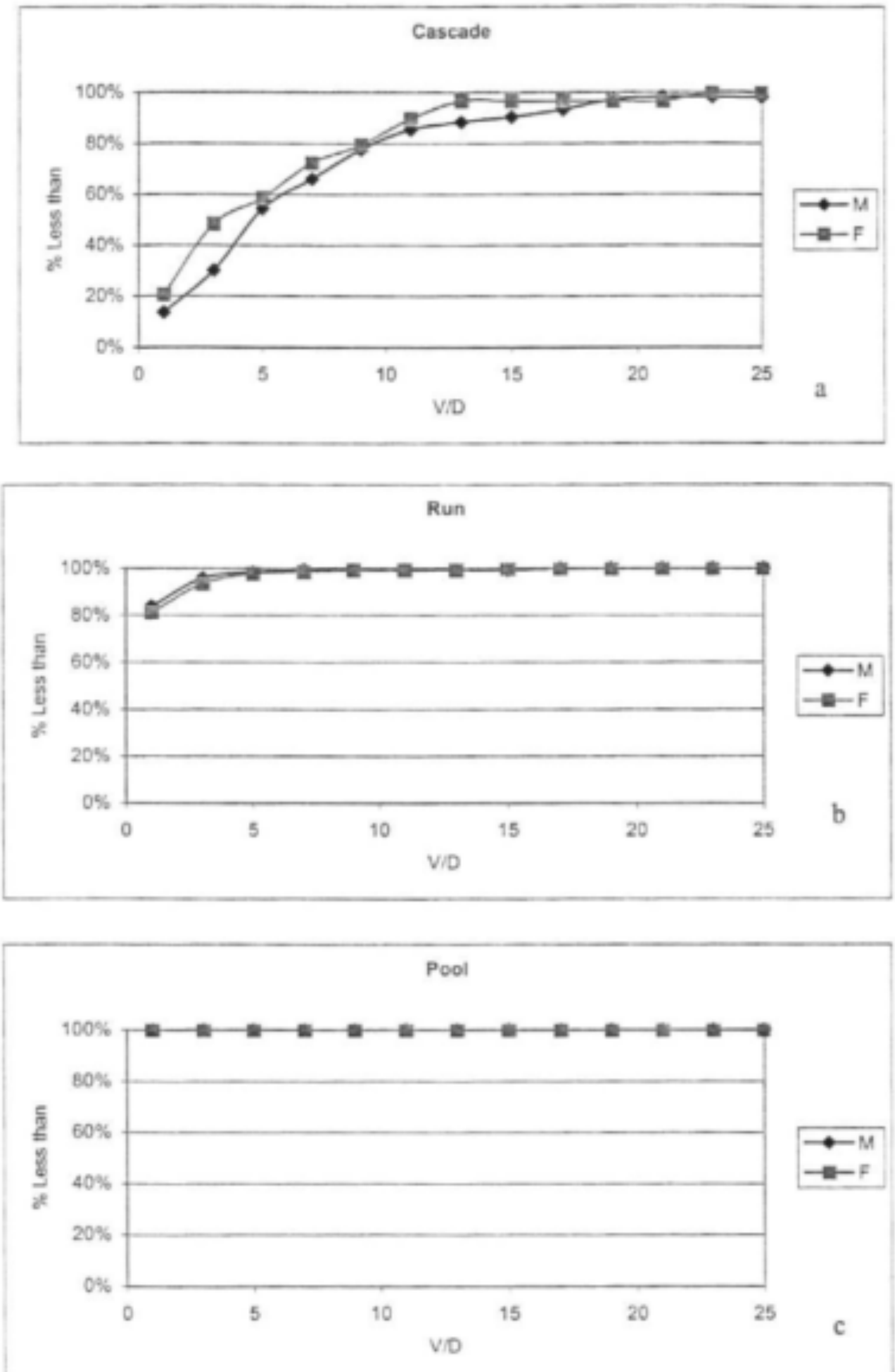


Figure 4 : Velocity/depth ratio probability distribution in hydraulic biotope classes (cont.)

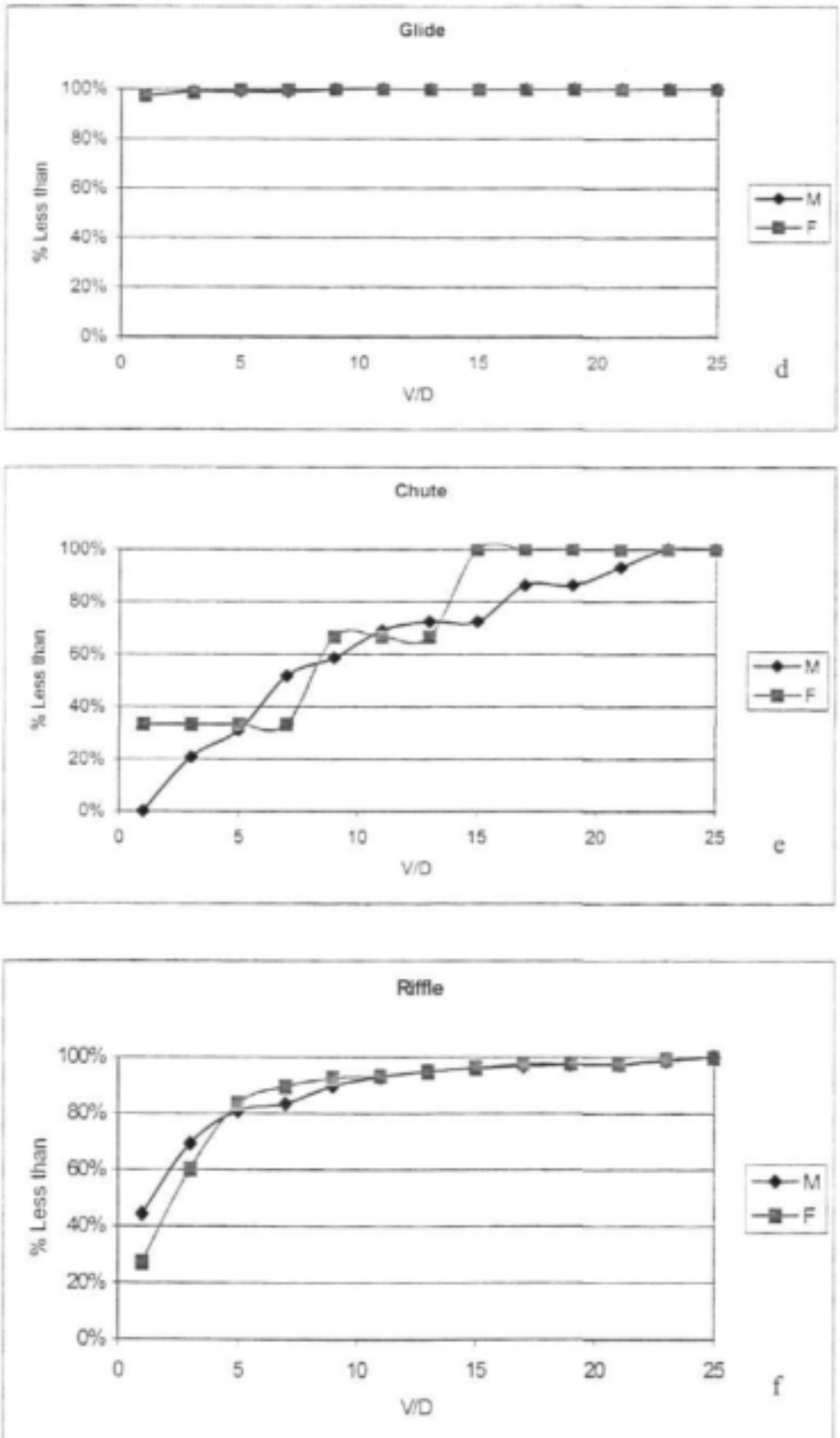


Figure 4 : Velocity/depth ratio probability distribution in hydraulic biotope classes (cont.)

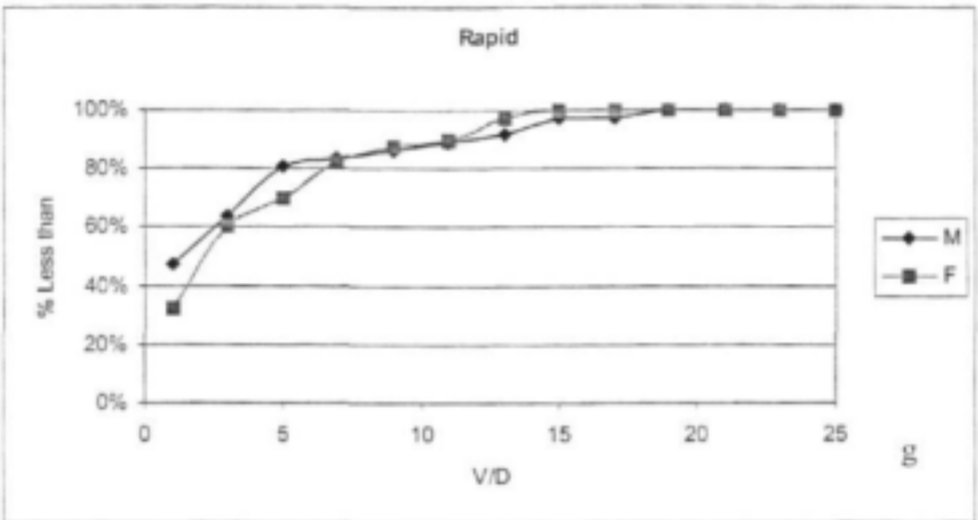
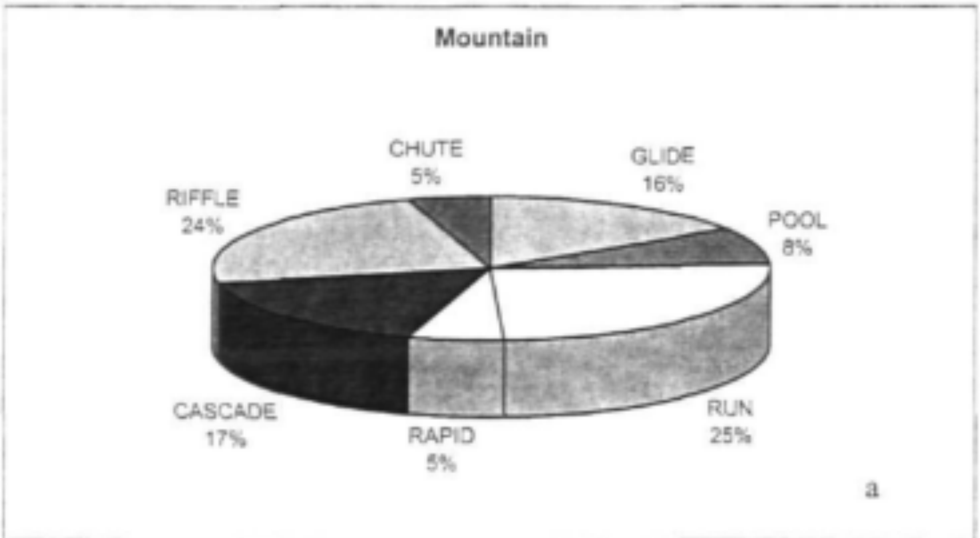


Figure 4 : Velocity/depth ratio probability distribution in hydraulic biotope classes (cont.)



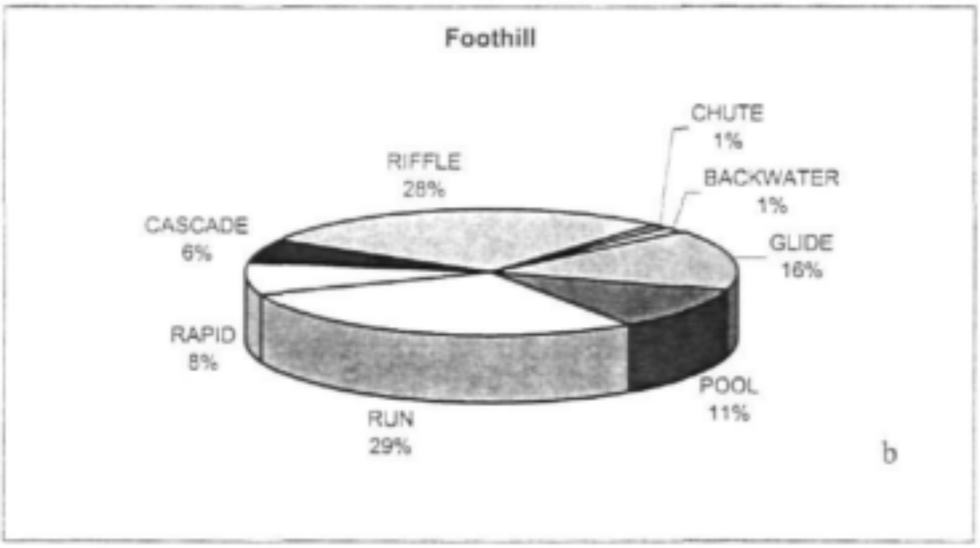


Figure 5 : Habitat diversity in mountain and foothill reaches

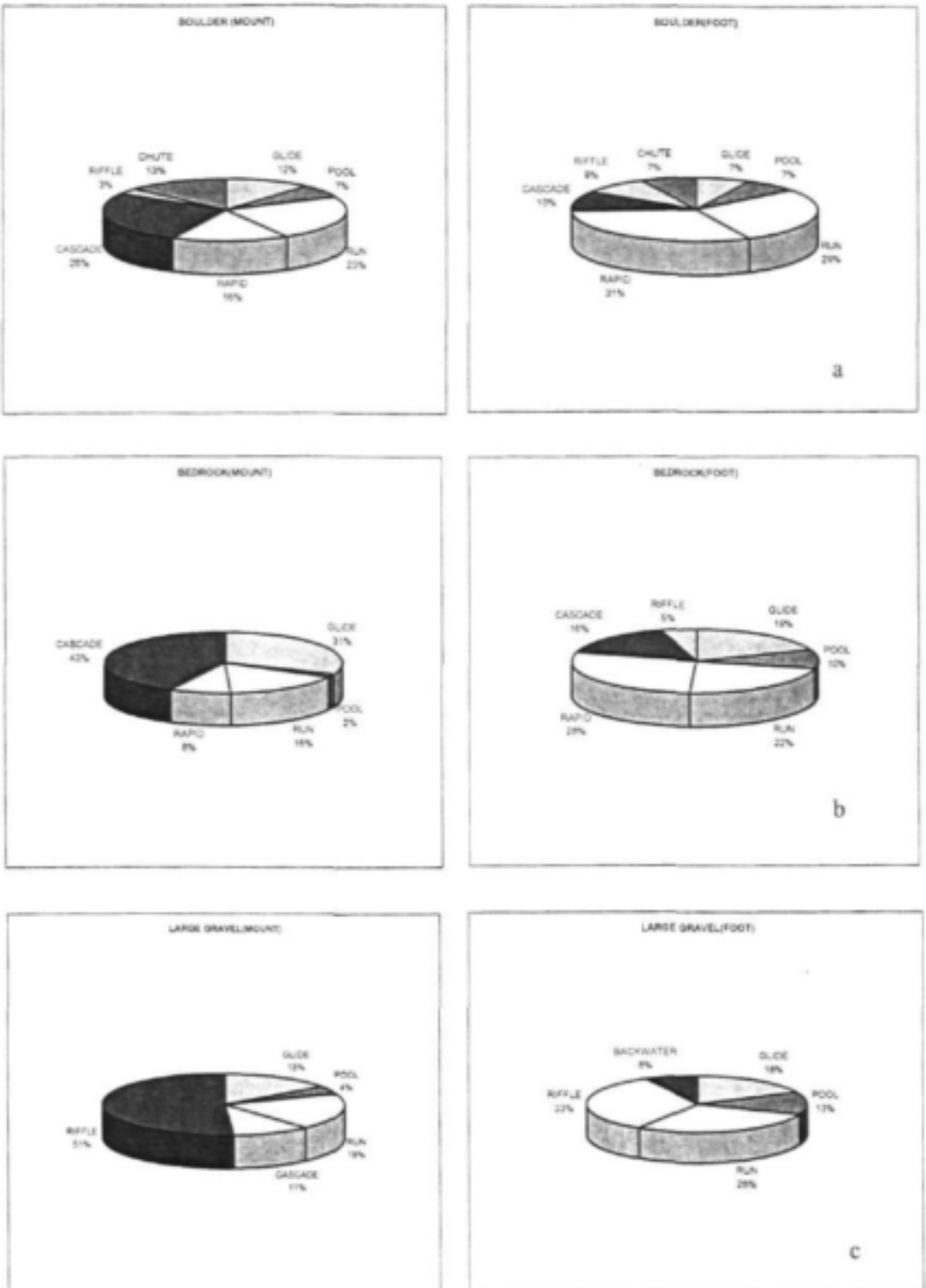


Figure 6 : Habitat diversity associated with substrate in mountain and foothill reaches

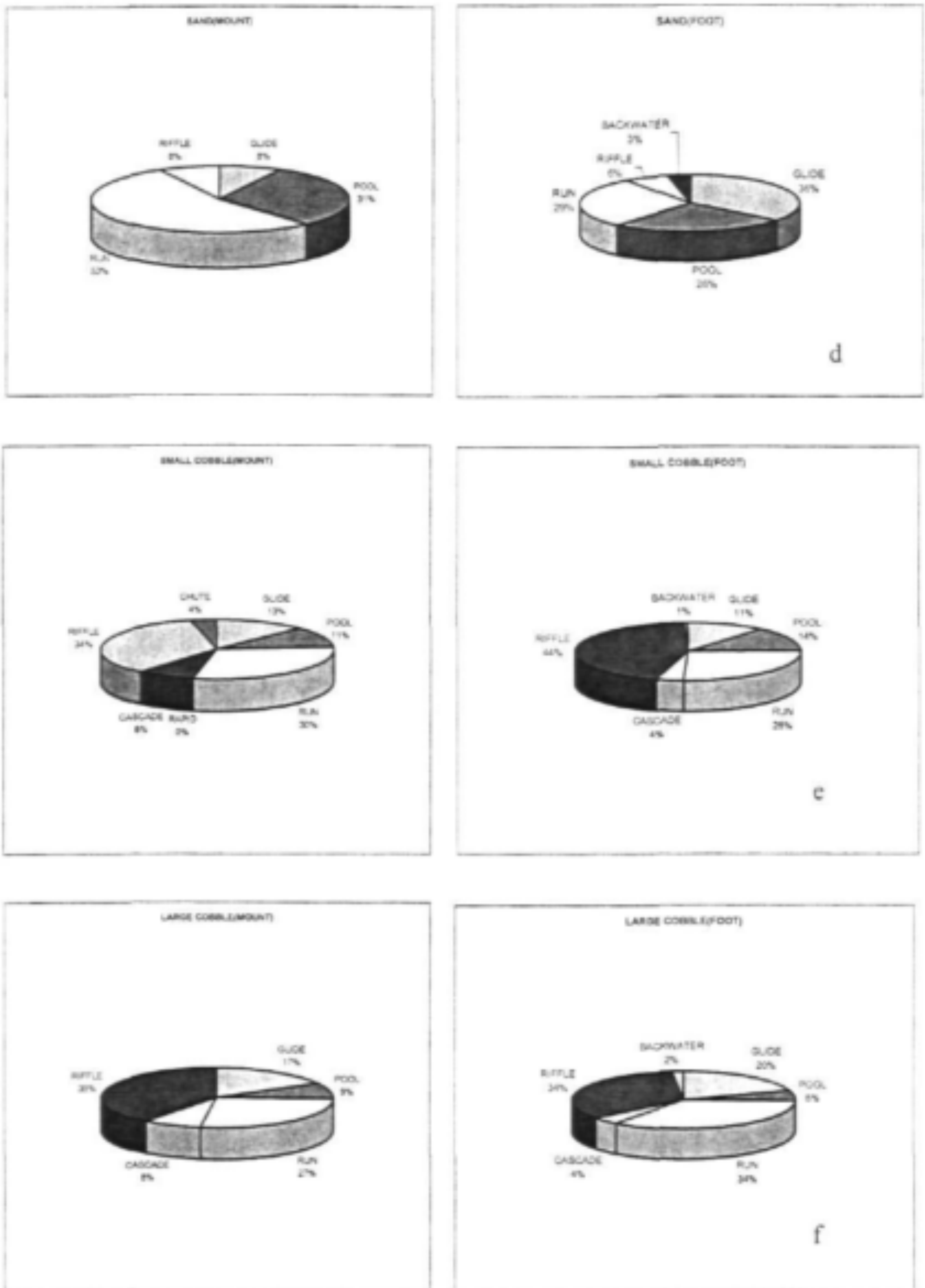
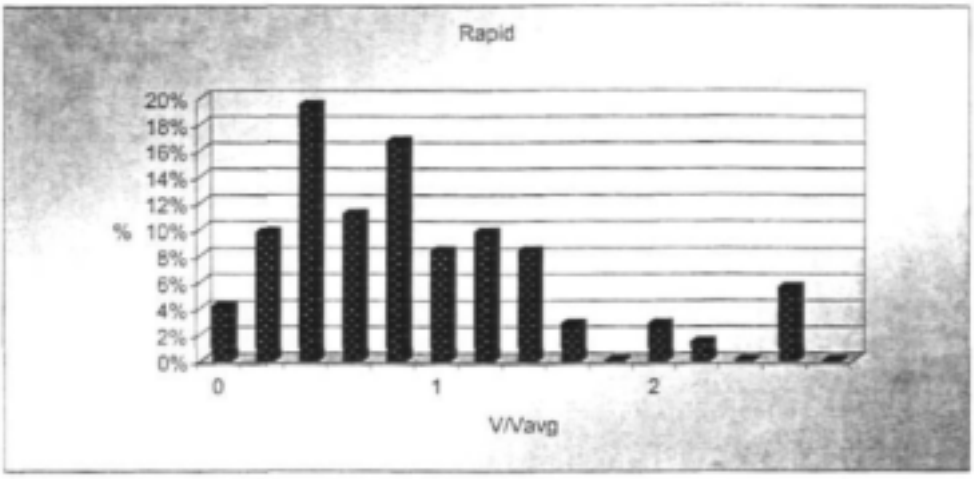
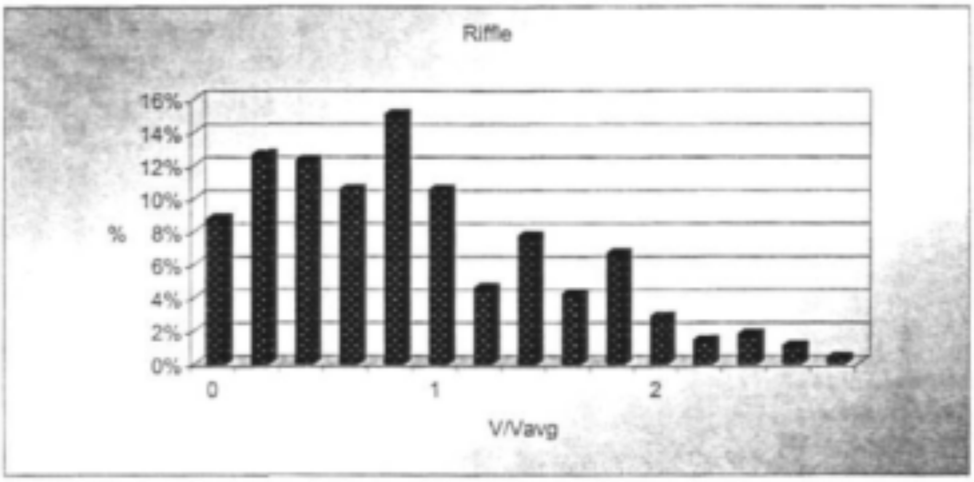


Figure 6: Habitat diversity associated with substrate in mountain and foothill reaches (cont.)





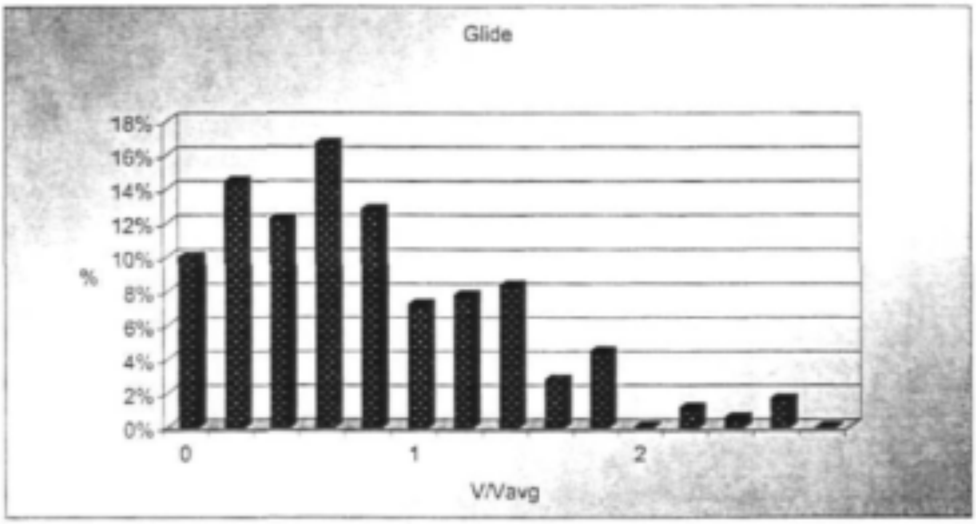


Figure 7: Point velocity frequency distribution across biotope classes

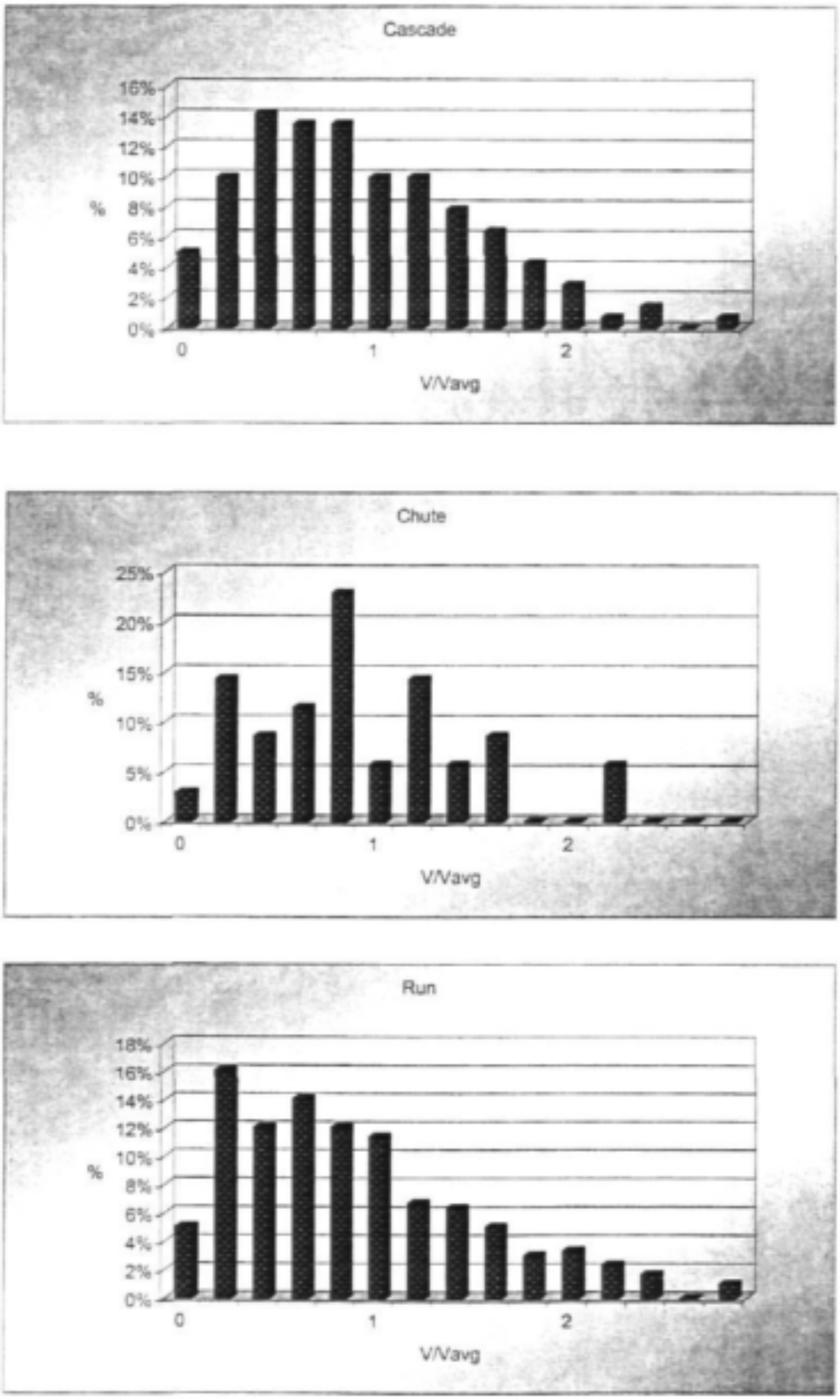


Figure 7: Point velocity frequency distribution across biotope classes (cont.)

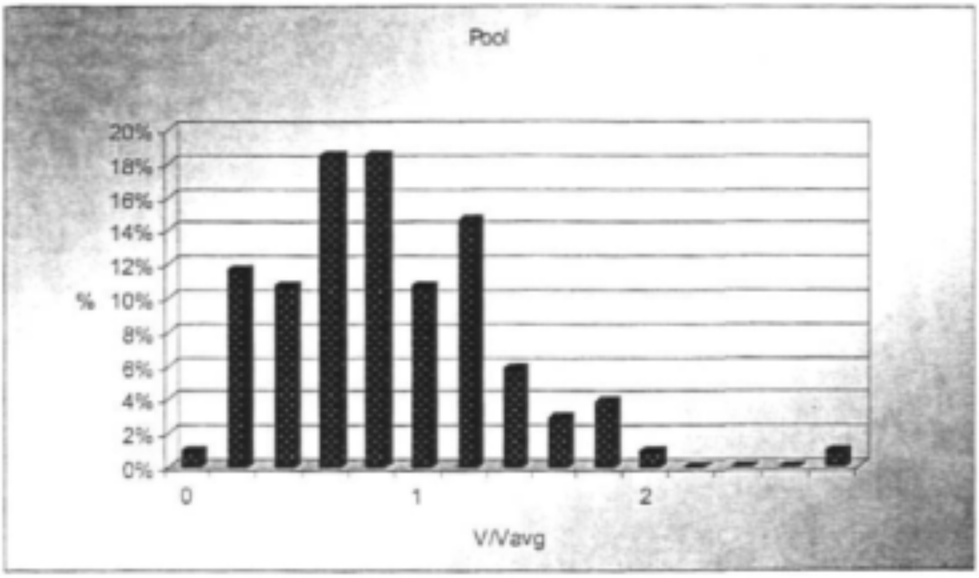


Figure 7: Point velocity frequency distribution across biotope classes (cont.)

APPENDIX B: Photographic record of study reaches

WHITEBRIDGE

JONKERSHOEK

VERGENOEG

VLOTTENBURG

ELANDS

SMALBLAAR

MOLENAARS I

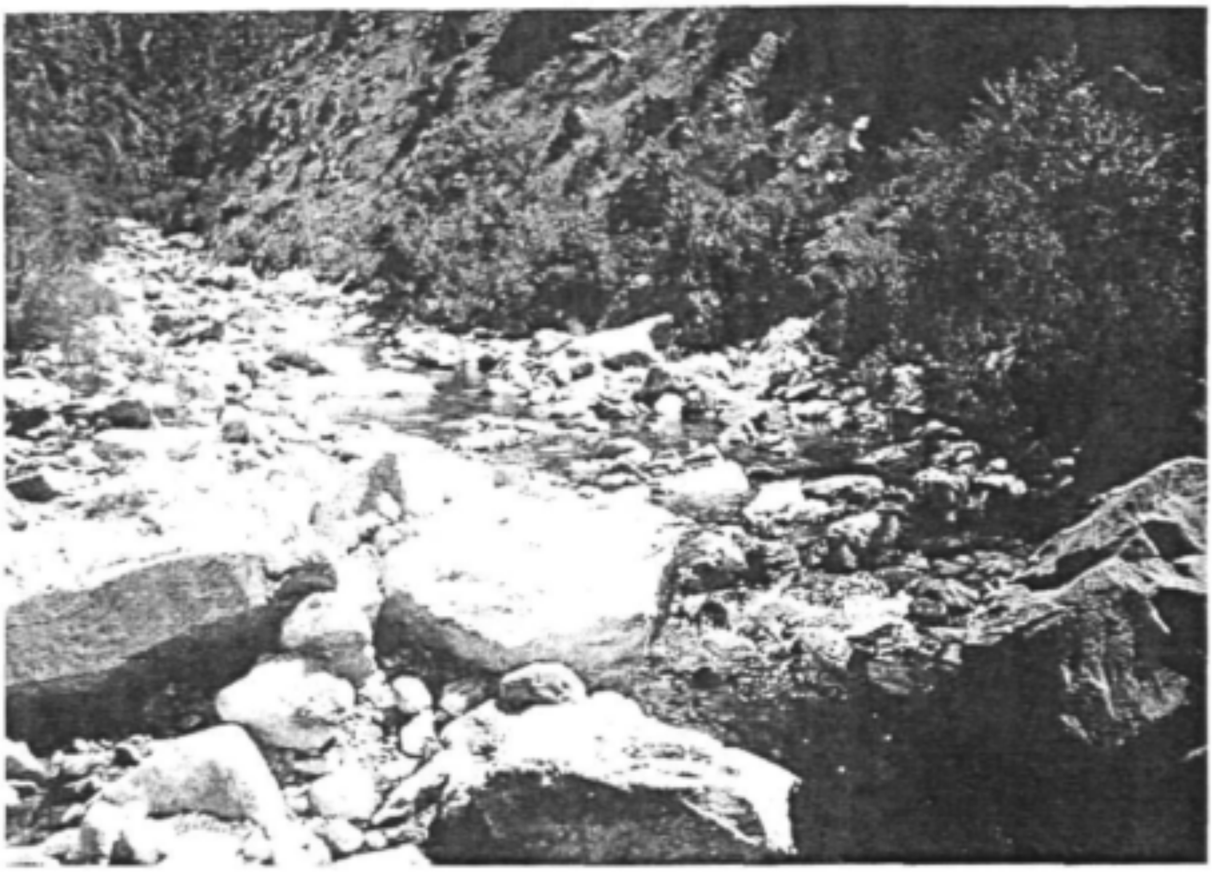
MOLENAARS II

BERG I

BERG II

BERG III

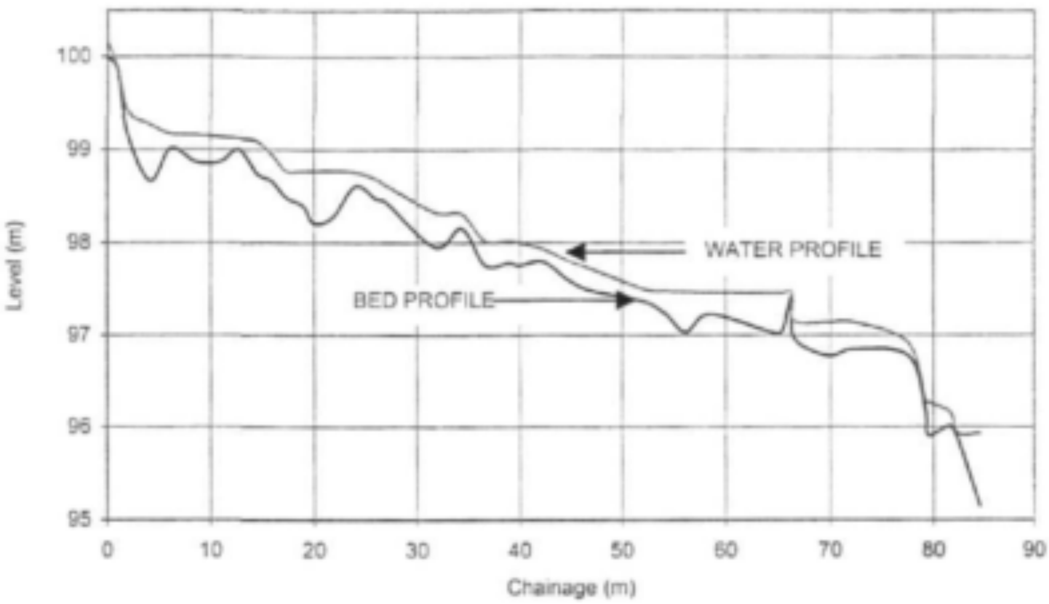
BERG IV



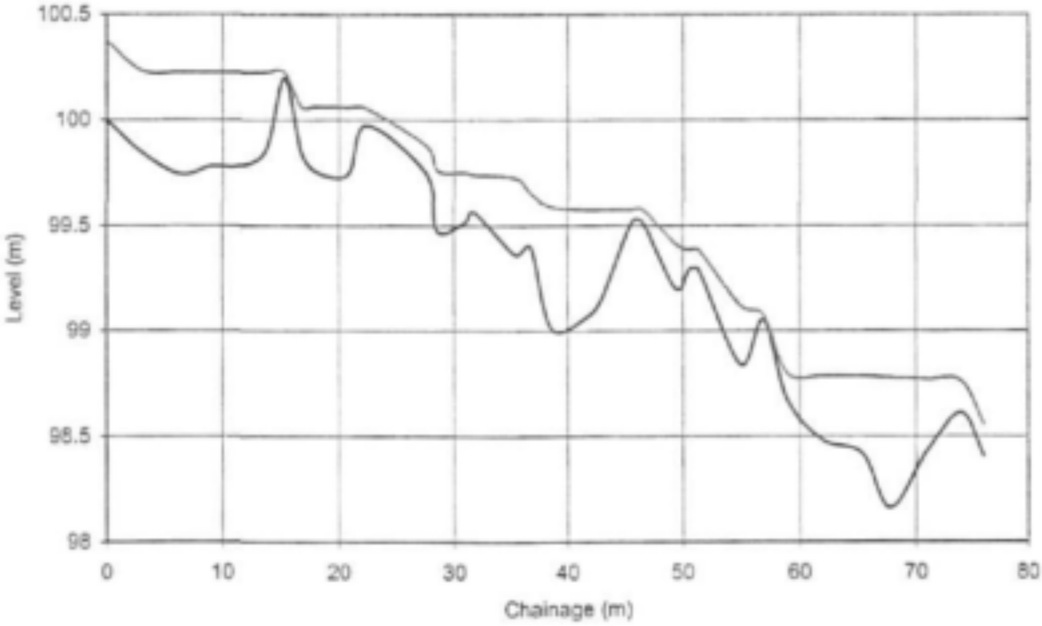
DU TOITS

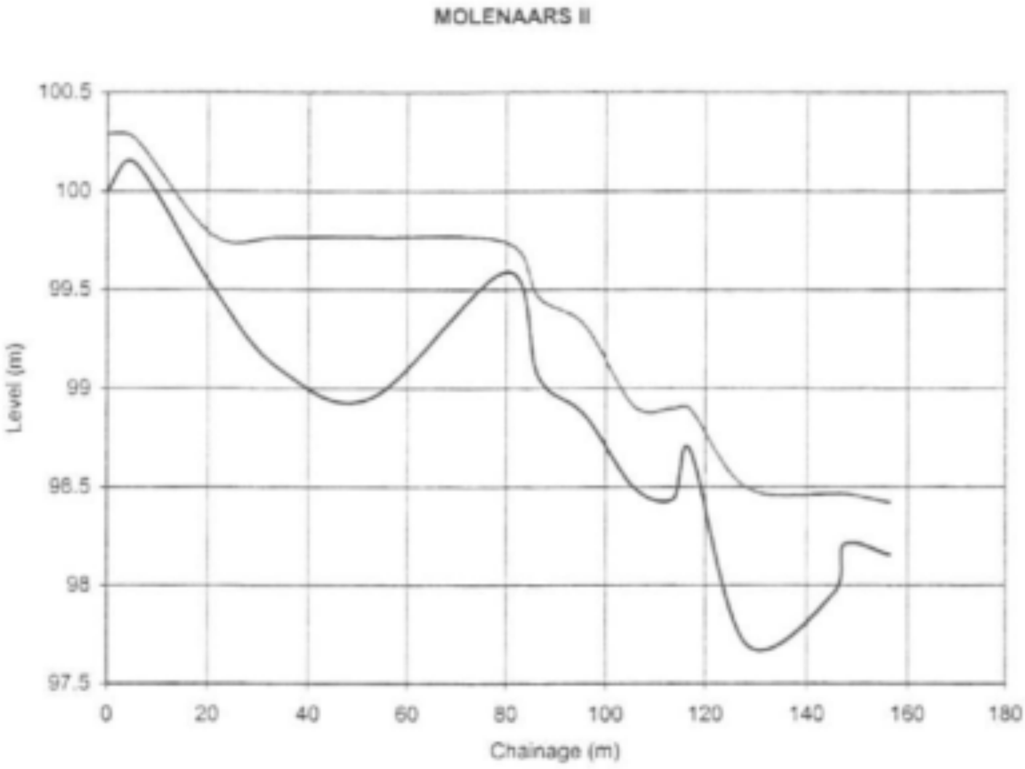
APPENDIX C: Longitudinal thalweg profiles

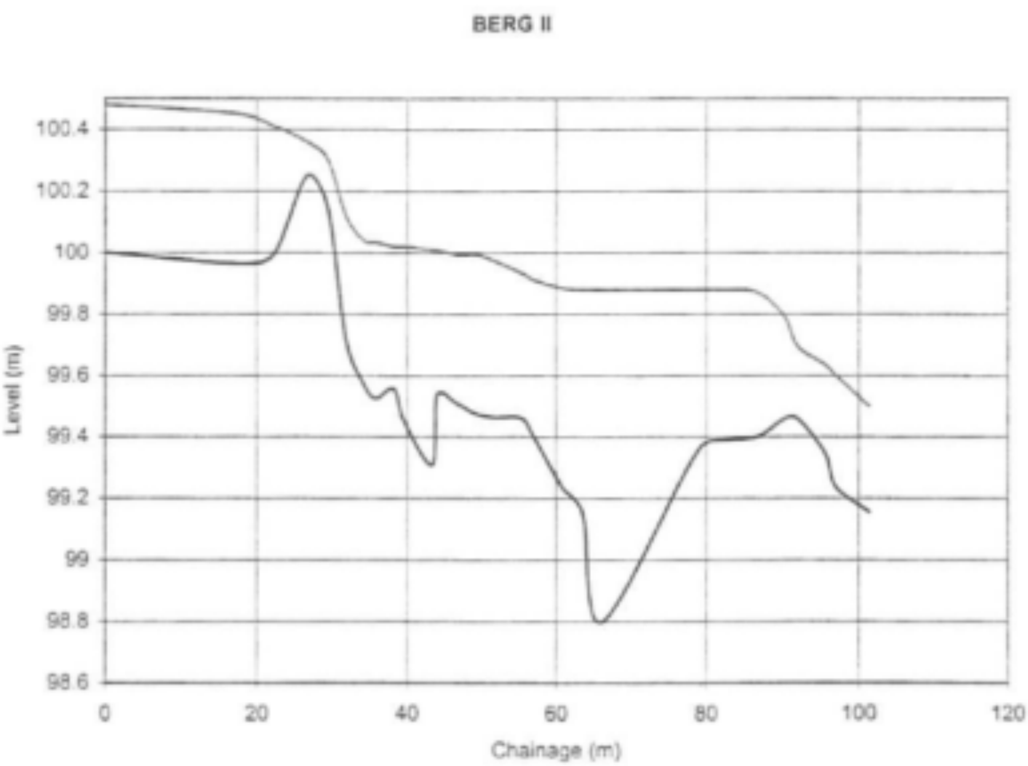
WHITEBRIDGE



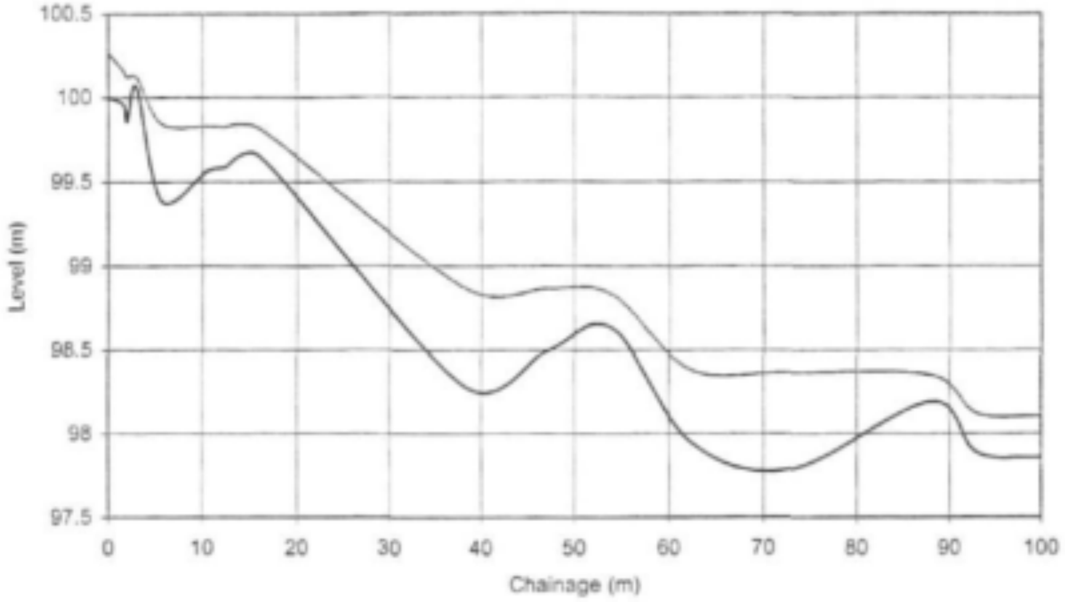
JONKERSHOEK



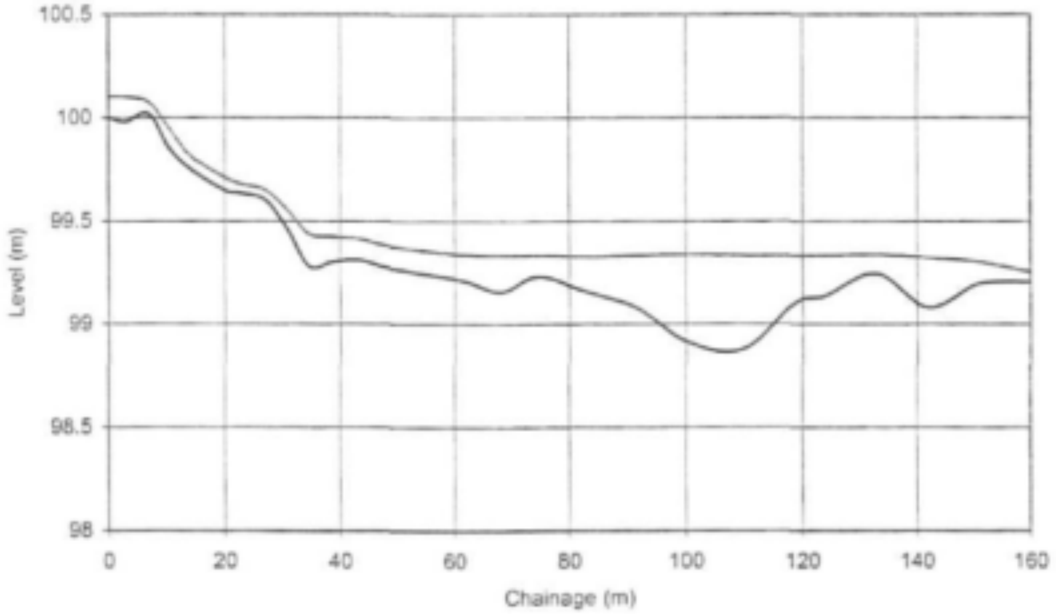

MOLENAARS II
100.5
100
99.5
99
98.5
98
97.5
Level (m)
0
20
40
60
80
100
120
140
160
180
Chainage (m)


BERG II
100.4
100.2
100
99.8
99.6
99.4
99.2
99
98.8
98.6
Level (m)
0
20
40
60
80
100
120
Chainage (m)

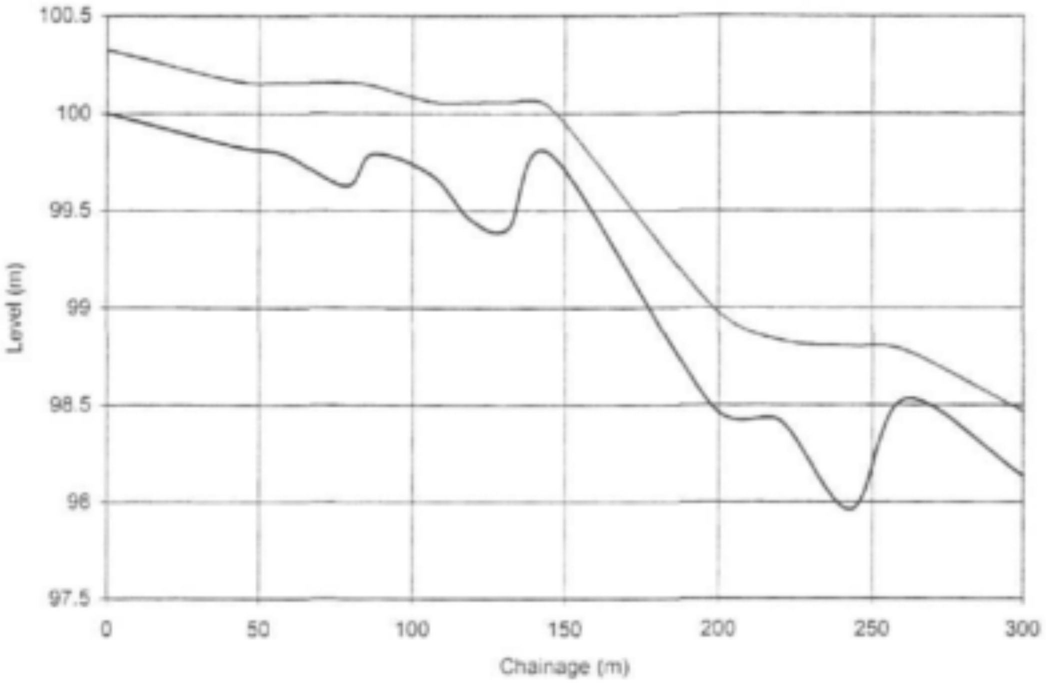
SMALBLAAR



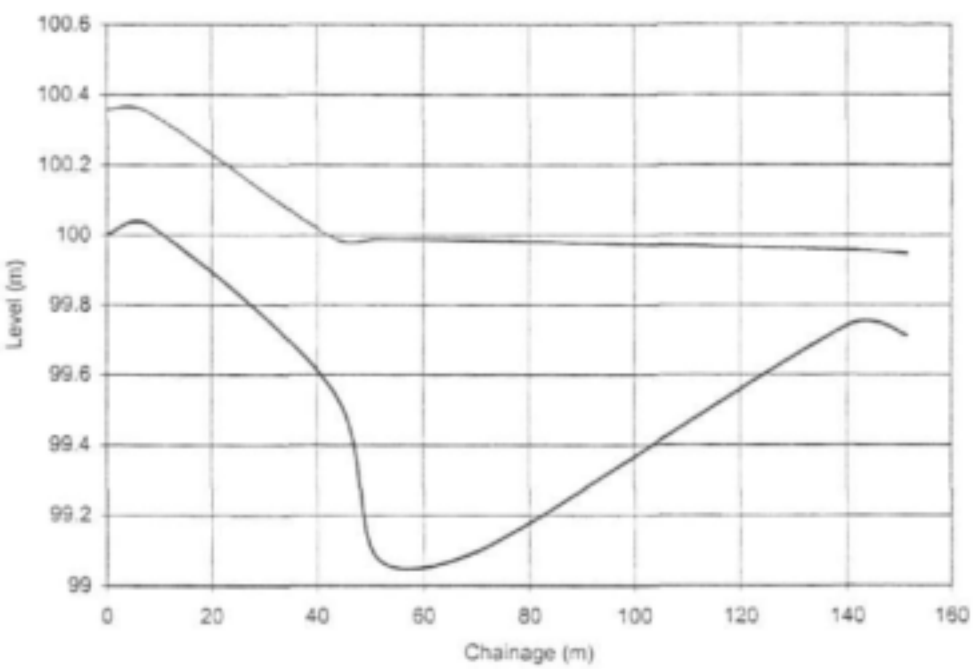
MOLENAARS I



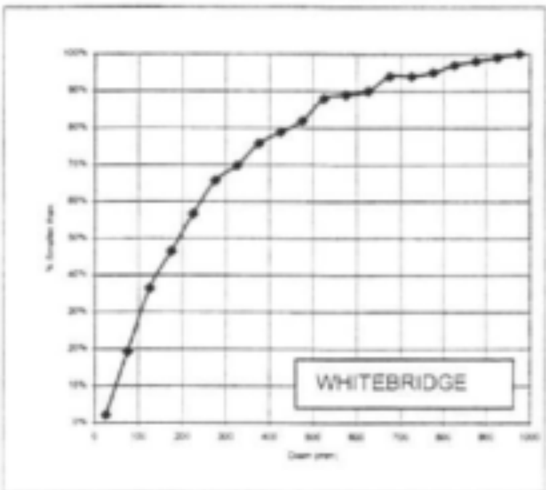
BERG III

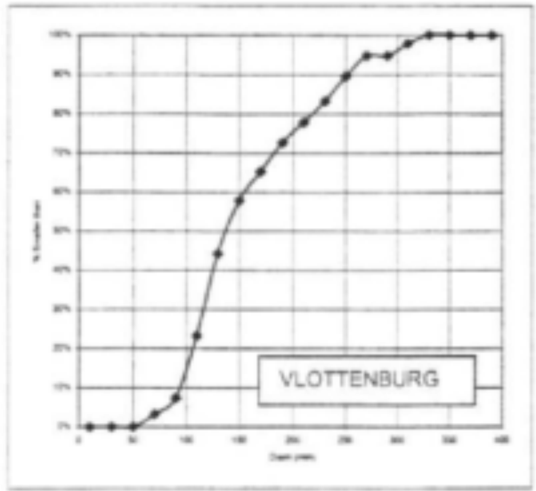


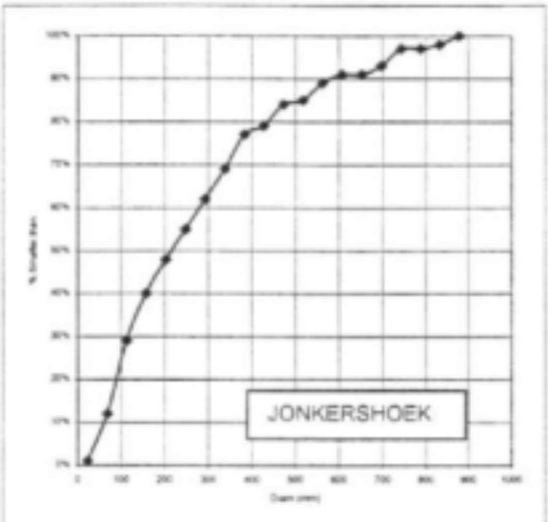
BERG IV

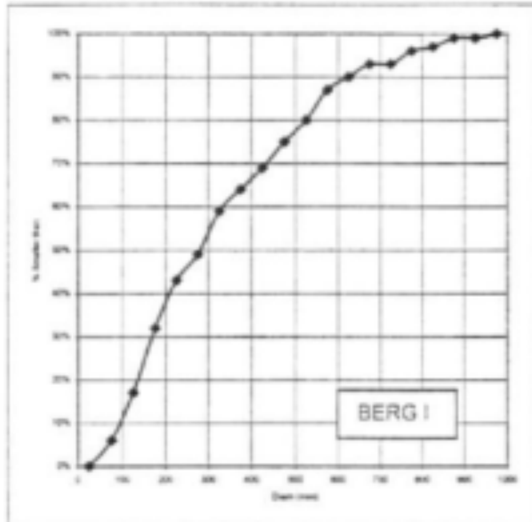


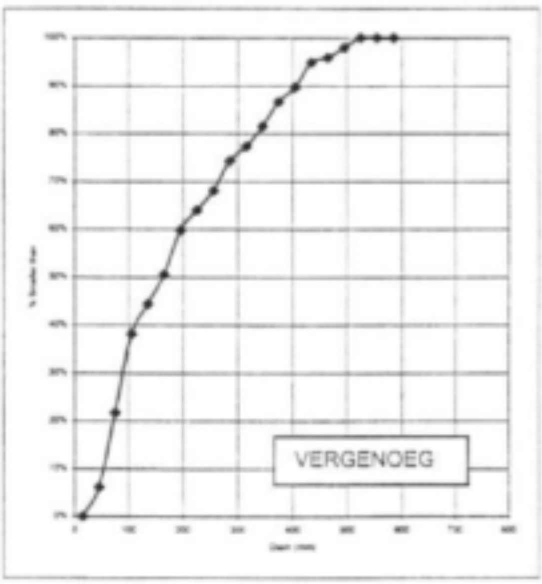
APPENDIX D: Substrate size distributions

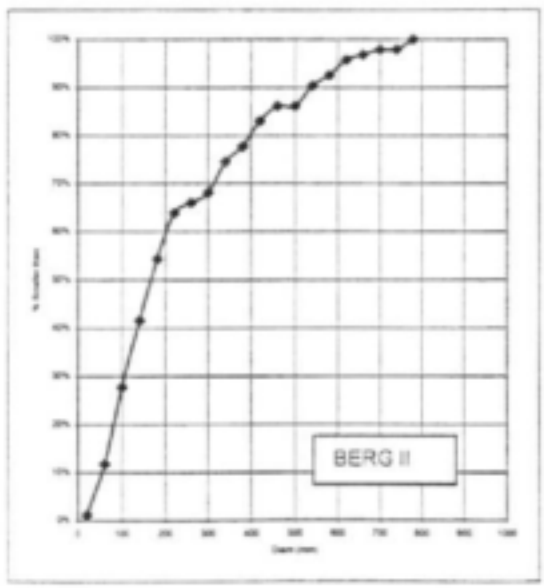

WHITEBRIDGE

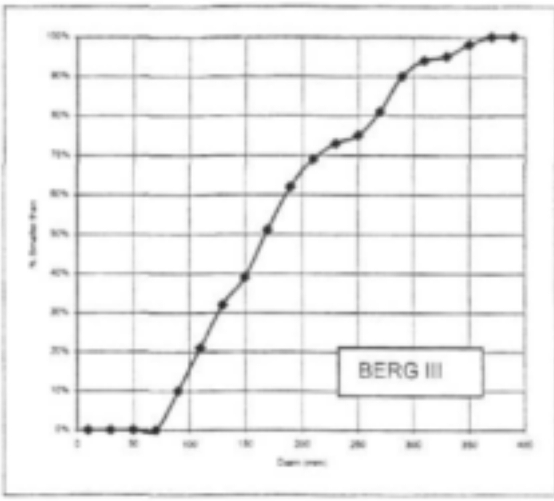

VLOTTENBURG

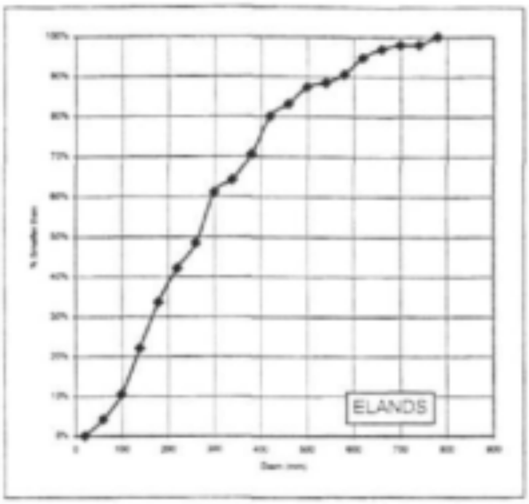

JONKERSHOEK

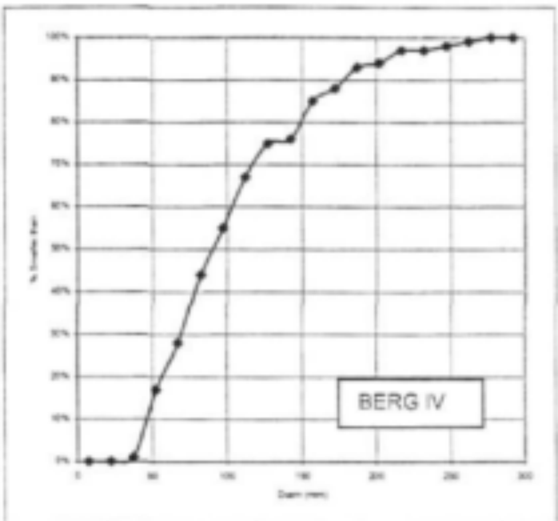

BERG I

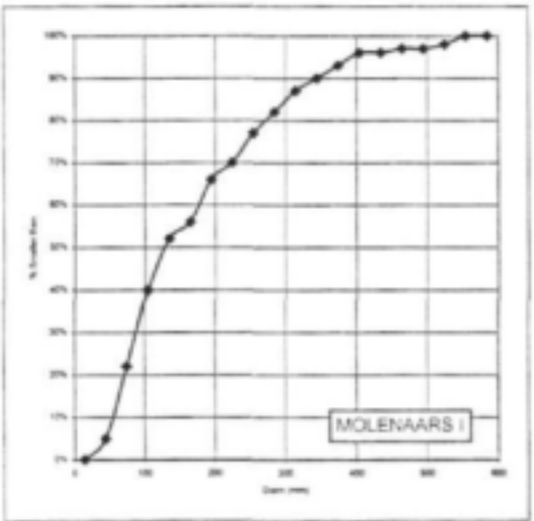

VERGENOEG

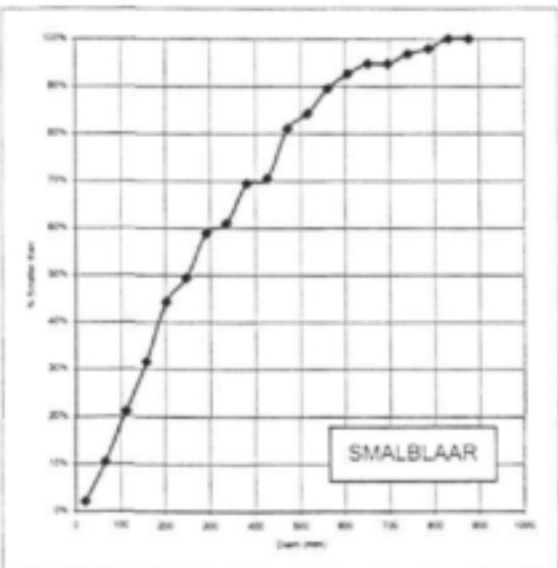

BERG II

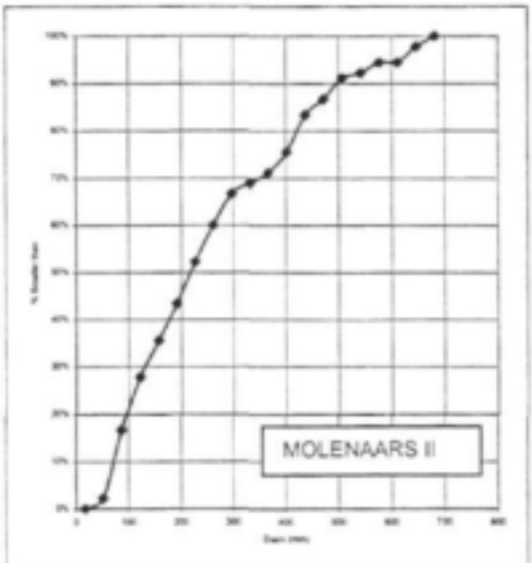

BERG III

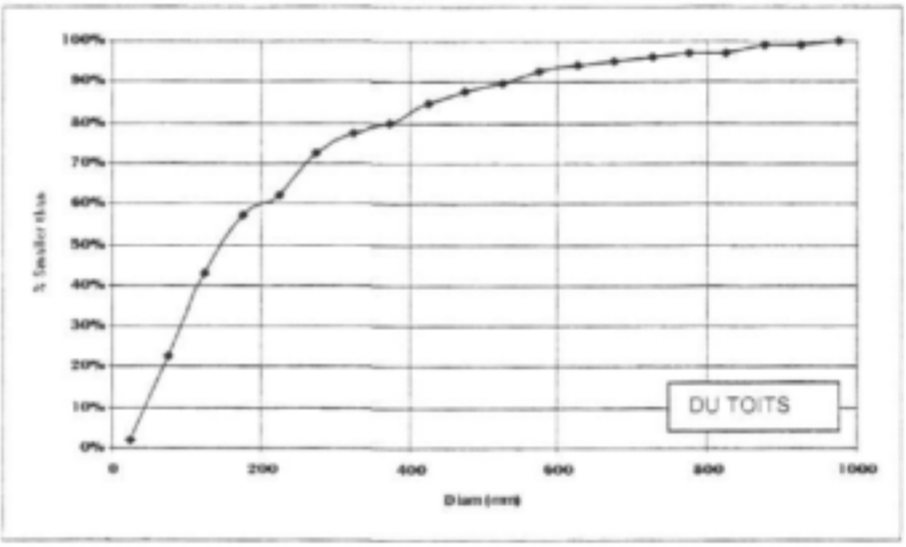

ELANDS


BERG IV

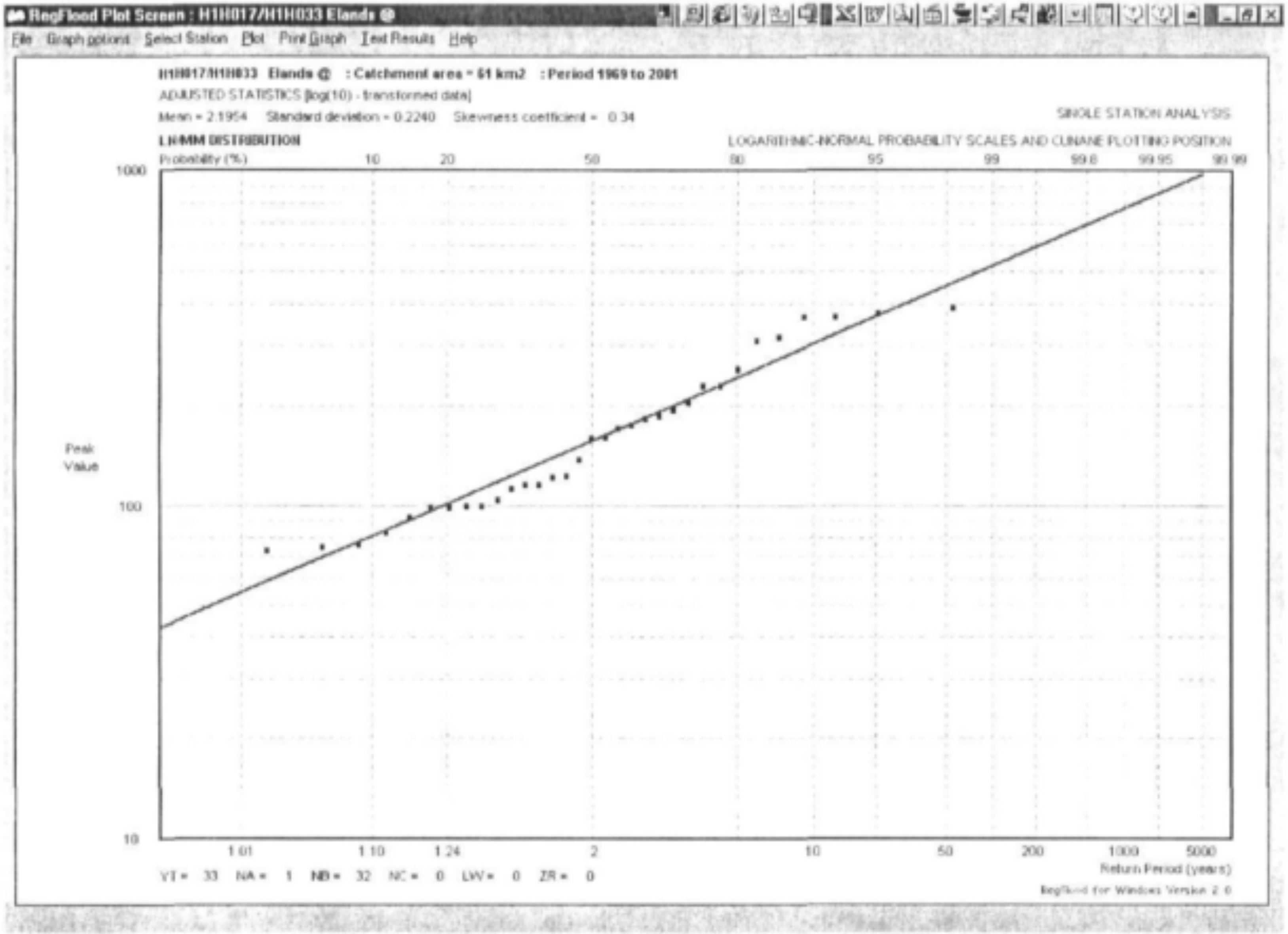

MOLENAARS I

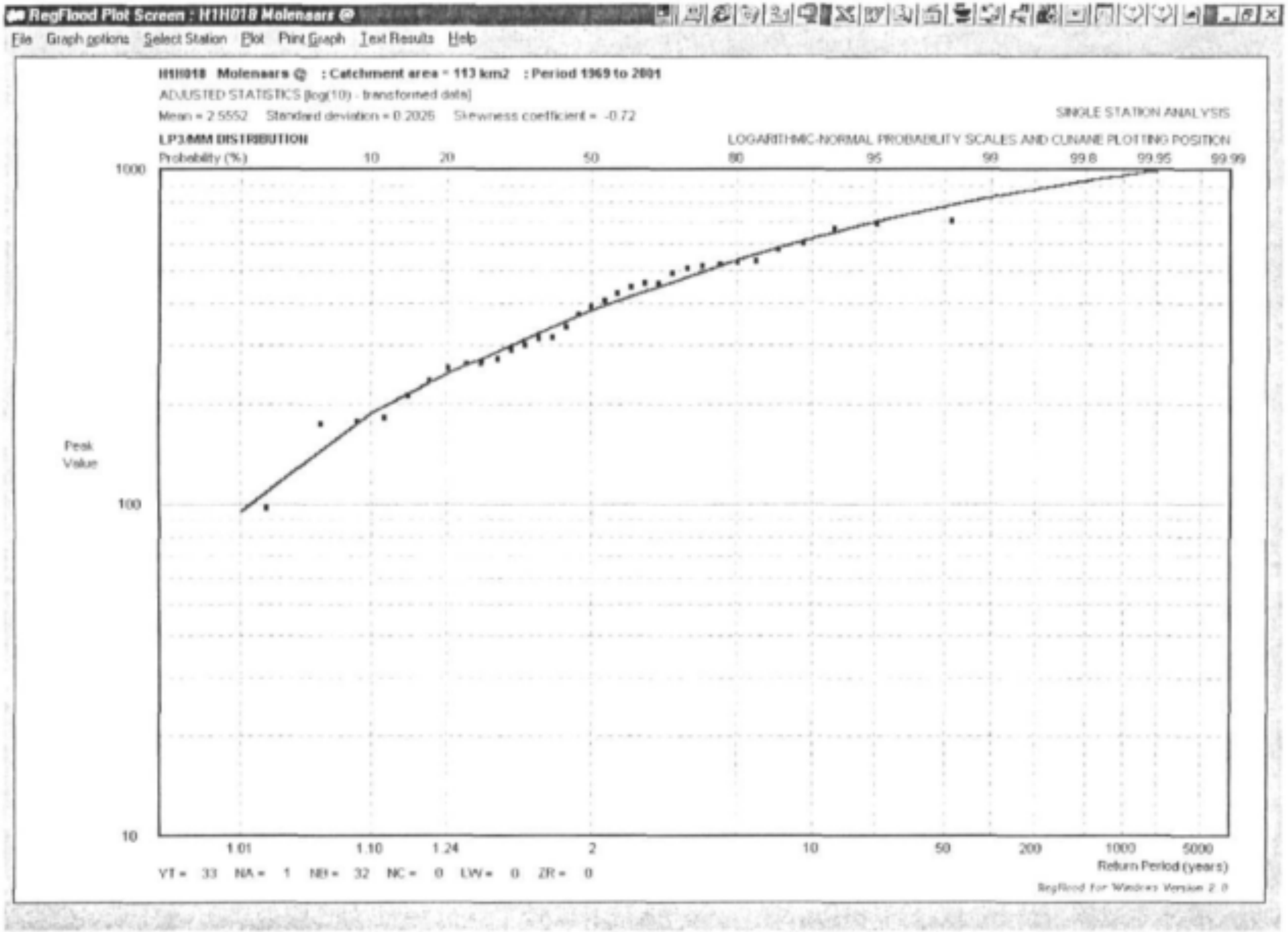

SMALBLAAR

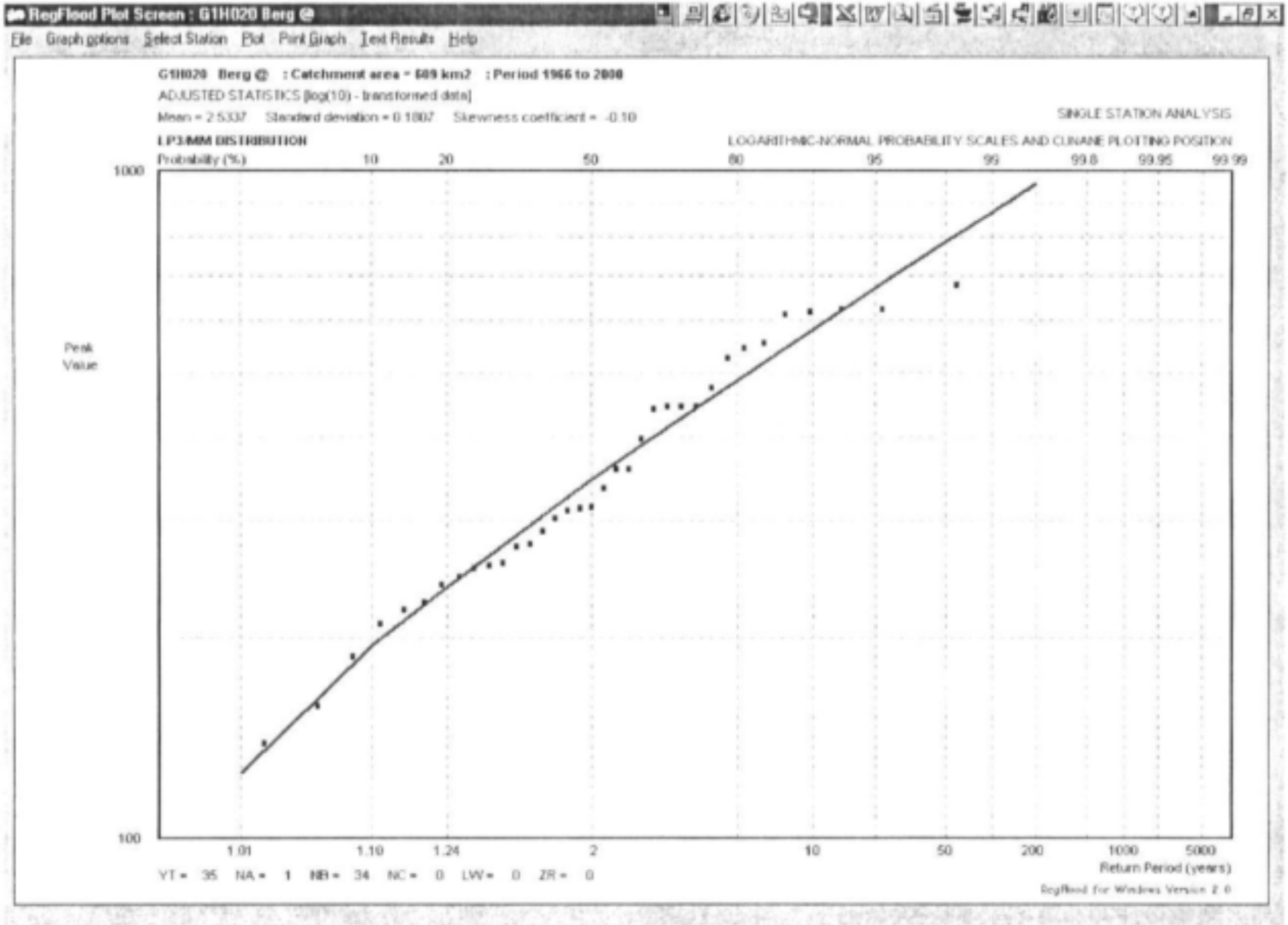

MOLENAARS II


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Smaller than
0
200
400
600
800
1000
Diam (mm)
DU TOITS

APPENDIX E: Flood frequency analysis results


RegFlood Plot Screen : H1H017/H1H033 Elands @
File Graph options Select Station Plot Print Graph Text Results Help
H1H017/H1H033 Elands @ : Catchment area = 61 km2 : Period 1969 to 2001
ADJUSTED STATISTICS [log(10) - transformed data]
Mean = 2.1954 Standard deviation = 0.2240 Skewness coefficient = 0.34
SINGLE STATION ANALYSIS
LH-MM DISTRIBUTION
LOGARITHMIC-NORMAL PROBABILITY SCALES AND CUNANE PLOTTING POSITION
Probability (%)
Peak Value
Return Period (years)
YT = 33 NA = 1 NB = 32 NC = 0 LW = 0 ZR = 0
RegFlood for Windows Version 2.0


RegFlood Plot Screen : H1H018 Molenaars @
File Graph options Select Station Plot Print Graph Text Results Help
H1H018 Molenaars @ : Catchment area = 113 km2 : Period 1969 to 2001
ADJUSTED STATISTICS (log(10) - transformed data)
Mean = 2.5552 Standard deviation = 0.2026 Skewness coefficient = -0.72
SINGLE STATION ANALYSIS
LP3/MM DISTRIBUTION
LOGARITHMIC-NORMAL PROBABILITY SCALES AND CUNANE PLOTTING POSITION
Probability (%)
10
20
50
80
95
99
99.8
99.95
99.99
1000
Peak Value
100
10
1.01
1.10
1.24
2
10
50
200
1000
5000
Return Period (years)
YT = 33 NA = 1 NB = 32 NC = 0 LW = 0 ZR = 0
RegFlood for Windows Version 2.0


RegFlood Plot Screen : G1H020 Berg @
File Graph options Select Station Plot Print Graph Text Results Help
G1H020 Berg @ : Catchment area = 609 km2 : Period 1966 to 2000
ADJUSTED STATISTICS [log(10) - transformed data]
Mean = 2.5337 Standard deviation = 0.1807 Skewness coefficient = -0.10
SINGLE STATION ANALYSIS
LP3/MM DISTRIBUTION
LOGARITHMIC-NORMAL PROBABILITY SCALES AND CUNANE PLOTTING POSITION
Probability (%) 10 20 50 80 95 99 99.8 99.95 99.99
1000
Peak Value
100
1.01 1.10 1.24 2 10 50 200 1000 5000
Return Period (years)
YT = 35 NA = 1 NB = 34 NC = 0 LW = 0 ZR = 0
RegFlood for Windows Version 2.0

APPENDIX F: Sand scour experimental results

SCOUR RATE DATA								
Exp No.	Time (min)	Scour level	Diameter Sand (m)	Diameter Cobble (m)	Avg. flow depth (m)	Discharge (m3/s)	Avg. velocity (m/s)	Scour depth (mm)
46	0	261						0
	25	251						10
	55	239	0.00054	0.08	0.200	0.109	0.545	22
	85	235						26
	105	231						30
47	0	268						0
	10	227						41
	20	219	0.00054	0.08	0.273	0.226	0.828	49
	40	215						53
	58	211						50
48	0	263						0
	20	240						23
	50	234	0.00054	0.08	0.406	0.237	0.584	26
	70	230						27
	90	228						29
49	0	269						0
	5	228						41
	10	218	0.00054	0.08	0.278	0.256	0.921	51
	30	210						59
	40	201						59
50	0	271						0
	10	255						16
	20	241	0.00054	0.08	0.567	0.333	0.587	30
	60	227						33
	110	224						36
51	0	268						0
	10	233						35
	30	224	0.00054	0.08	0.405	0.387	0.956	44
	50	216						46
52	0	267						0
	5	255						12
	35	241	0.00054	0.08	0.448	0.346	0.772	26
	55	232						35
	75	223						44
	95	216						45
53	0	260						0
	10	244						16
	20	228	0.00054	0.08	0.698	0.525	0.752	32
	50	221						39
	90	219						42

SCOUR RATE DATA (cont.)							
		Diameter		Avg. flow		Avg.	Scour
Exp No.	Time	Sand	Cobble	depth	Discharge	velocity	depth
	(min)	(m)	(m)	(m)	(m3/s)	(m/s)	(mm)
57	0						0
	5						73
	12	0.00054	0.130	0.339	0.332	0.979	80
	19						85
	30						91
	35						94
56	0						0
	7						35
	21	0.00054	0.130	0.308	0.236	0.766	67
	37						71
55	0						0
	6						2
	20						20
	45	0.00054	0.130	0.289	0.162	0.561	35
	60						45
	80						50
	90						53
61	0						0
	15						12
	20						21
	24	0.00022	0.130	0.235	0.120	0.511	28
	28						31
	34						33
	38						36
62	0						0
	5						11
	8						32
	12						42
	17	0.00022	0.130	0.268	0.160	0.597	43
	22						45
	32						48
	45						52
63	0						0
	3						4
	7						21
	9	0.00022	0.130	0.340	0.243	0.715	28
	11						33
	14						41
	17						45
	30						64

MAXIMUM SCOUR DEPTHS / EQUILIBRIUM SCOUR RESULTS							
No.	Diameter		Flow				*Scour
	Sand (m)	Cobble (m)	Depth (m)	Discharge (m3/s)	*Time (min)	Velocity (m/s)	Depth (m)
1	0.00022	0.06	0.400	0.200	70	0.500	0.008
2	0.00022	0.06	0.071	0.025	45	0.354	0.015
3	0.00022	0.06	0.600	0.300	90	0.500	0.015
4	0.00022	0.06	0.200	0.100	105	0.500	0.030
5	0.00022	0.06	0.500	0.300	55	0.600	0.030
6	0.00022	0.06	0.600	0.400	50	0.667	0.040
7	0.00022	0.06	0.800	0.600	45	0.750	0.040
8	0.00022	0.06	0.107	0.050	75	0.467	0.045
9	0.00022	0.06	0.150	0.100	50	0.667	0.045
10	0.00022	0.06	0.300	0.200	50	0.667	0.045
11	0.00022	0.06	0.800	0.500	85	0.625	0.045
12	0.00022	0.06	0.250	0.200	35	0.800	0.060
13	0.00022	0.06	0.400	0.300	40	0.750	0.060
14	0.00022	0.06	0.500	0.400	45	0.800	0.060
15	0.00022	0.06	0.600	0.500	35	0.833	0.060
16	0.00022	0.06	0.300	0.300	45	1.000	0.060
17	0.00022	0.06	0.501	0.500	60	0.998	0.060
18	0.00022	0.06	0.600	0.600	40	1.000	0.060
19	0.00022	0.06	0.400	0.400	35	1.000	0.060
20	0.00022	0.06	0.500	0.600	40	1.200	0.060
21	0.00022	0.06	0.407	0.500	35	1.229	0.060
22	0.00022	0.071	0.123	0.050	40	0.406	0.036
23	0.00022	0.071	0.201	0.099	45	0.494	0.036
24	0.00022	0.071	0.400	0.200	70	0.500	0.036
25	0.00022	0.071	0.804	0.502	75	0.624	0.053
26	0.00022	0.071	0.299	0.200	55	0.669	0.071
27	0.00022	0.071	0.601	0.403	40	0.671	0.071
28	0.00022	0.071	0.600	0.499	60	0.832	0.071
29	0.00022	0.071	0.150	0.100	48	0.667	0.071
30	0.00022	0.071	0.251	0.200	38	0.797	0.071
31	0.00022	0.071	0.502	0.403	45	0.802	0.071
32	0.00022	0.071	0.402	0.403	45	1.003	0.071
33	0.00083	0.06	0.305	0.200	46	0.656	0.020
34	0.00083	0.06	0.499	0.295	51	0.592	0.020
35	0.00083	0.06	0.703	0.505	50	0.718	0.020
36	0.00083	0.06	0.400	0.295	41	0.738	0.030
37	0.00083	0.06	0.599	0.394	39	0.658	0.030
38	0.00083	0.06	0.601	0.505	48	0.841	0.030
39	0.00083	0.06	0.501	0.394	41	0.786	0.040
40	0.00083	0.06	0.709	0.600	50	0.846	0.040
41	0.00083	0.06	0.397	0.394	39	0.992	0.045
42	0.00083	0.06	0.502	0.505	42	1.006	0.045
43	0.00083	0.06	0.303	0.295	48	0.973	0.060
44	0.00083	0.06	0.603	0.600	37	0.995	0.060
45	0.00083	0.06	0.497	0.602	34	1.212	0.060
46	0.00054	0.08	0.200	0.109	105	0.545	0.029
47	0.00054	0.08	0.273	0.226	58	0.828	0.049
48	0.00054	0.08	0.406	0.237	90	0.584	0.028
49	0.00054	0.08	0.278	0.256	35	0.921	0.059
50	0.00054	0.08	0.567	0.333	110	0.587	0.036
51	0.00054	0.08	0.405	0.387	50	0.956	0.046
52	0.00054	0.08	0.448	0.346	95	0.772	0.045
53	0.00054	0.08	0.698	0.525	90	0.752	0.042
54	0.00054	0.08	0.374	0.465	-	1.243	0.080
55	0.00054	0.13	0.289	0.162	90	0.561	0.053
56	0.00054	0.13	0.308	0.236	40	0.766	0.071
57	0.00054	0.13	0.339	0.332	35	0.979	0.095
58	0.00054	0.13	0.321	0.186	-	0.579	0.041
59	0.00054	0.13	0.320	0.228	-	0.713	0.063
60	0.00054	0.13	0.399	0.530	-	1.328	0.122
61	0.00022	0.13	0.235	0.120	40	0.511	0.036
62	0.00022	0.13	0.268	0.160	45	0.597	0.053
63	0.00022	0.13	0.340	0.243	30	0.715	0.064
64	0.00022	0.13	0.399	0.390	-	0.977	0.121

*Equilibrium

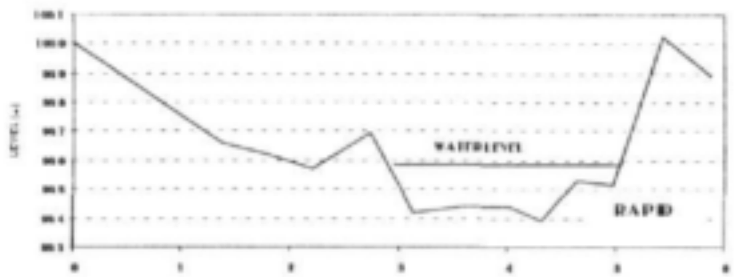
APPENDIX G: Large scale roughness data from literature

Reference	d50 (m)	Q(m3/s)	Area (m2)	R(m)	Sf(%)
Bathurst(1978)	0.28	0.90	2.46	0.17	1.74
	0.28	3.90	5.62	0.31	1.71
	0.28	7.20	8.04	0.40	1.66
	0.21	1.37	5.59	0.21	1.14
	0.21	4.00	8.98	0.28	1.15
	0.21	7.10	11.32	0.34	1.16
	0.19	1.10	3.72	0.20	0.80
	0.19	4.00	7.42	0.33	0.81
	0.19	7.10	9.45	0.40	0.81
Bathurst (1985)	0.34	6.74	12.30	0.46	1.28
	0.34	10.30	15.50	0.57	1.28
	0.34	23.30	24.20	0.88	1.56
	0.26	2.00	3.81	0.28	3.73
	0.26	2.69	4.36	0.30	3.60
	0.26	15.90	10.80	0.63	3.14
	0.26	24.80	15.80	0.84	3.64
	0.13	2.07	4.58	0.30	1.30
	0.13	3.30	6.22	0.40	1.06
	0.13	12.20	10.70	0.66	1.19
	0.13	25.50	13.60	0.83	1.13
	0.13	31.60	14.80	0.89	1.54
	0.13	102.00	27.40	1.31	1.06
	0.09	0.62	1.97	0.14	0.50
	0.09	11.30	6.96	0.47	0.83
	0.09	76.90	21.50	0.96	1.04
Thorne & Zev. (1985)	0.16	2.05	3.67	0.35	1.43
	0.16	3.28	4.37	0.40	1.51
	0.16	5.27	5.32	0.47	1.63
	0.16	8.64	6.71	0.57	1.47
	0.16	10.45	7.38	0.62	1.46
	0.13	2.05	3.96	0.29	1.83
	0.13	3.34	4.70	0.33	1.93
	0.13	4.28	5.10	0.35	1.89
	0.13	5.27	5.92	0.39	1.90
	0.13	6.91	6.85	0.49	1.85
	0.13	8.64	7.27	0.45	1.94
	0.13	10.45	8.22	0.50	1.98
Jarret (1984)	0.18	1.50	4.00	0.31	1.50
	0.18	6.06	6.60	0.46	1.70
	0.18	10.20	9.48	0.61	1.80
	0.18	21.67	13.11	0.79	1.90
	0.15	0.88	1.95	0.27	3.00
	0.15	3.26	3.35	0.37	3.40
	0.15	7.96	4.00	0.46	3.30
	0.30	4.19	6.32	0.37	1.90
	0.30	23.51	13.66	0.65	2.30
	0.30	38.53	17.20	0.77	2.40
	0.12	1.36	2.97	0.18	2.80
	0.12	2.61	4.28	0.24	2.60
	0.12	9.38	8.46	0.43	2.50
	0.12	11.59	11.81	0.59	2.10
	0.43	26.20	23.15	0.99	2.60
	0.43	41.08	31.60	1.22	2.30
	0.43	60.06	37.83	1.36	2.10
	0.43	78.19	42.20	1.48	2.50
	0.43	128.33	48.89	1.68	2.80
	0.12	5.78	11.43	0.37	0.30
	0.12	6.35	11.62	0.41	0.40
	0.12	6.60	12.55	0.43	0.40
	0.12	16.35	21.01	0.62	0.40
	0.12	65.16	41.18	1.07	0.40
	0.12	105.10	49.08	1.23	0.40

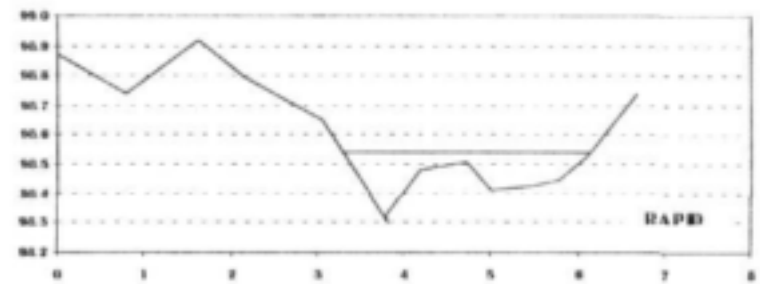
APPENDIX H: Cross sections

Whitebridge

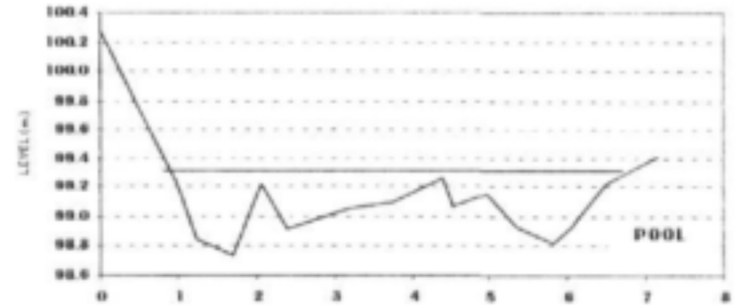
CROSS SECTION NO. 1



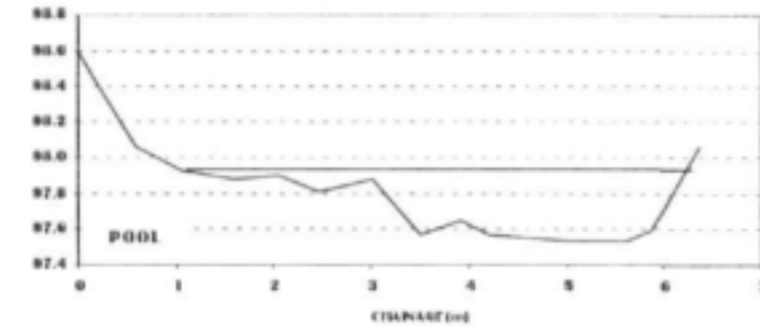
CROSS SECTION NO. 4



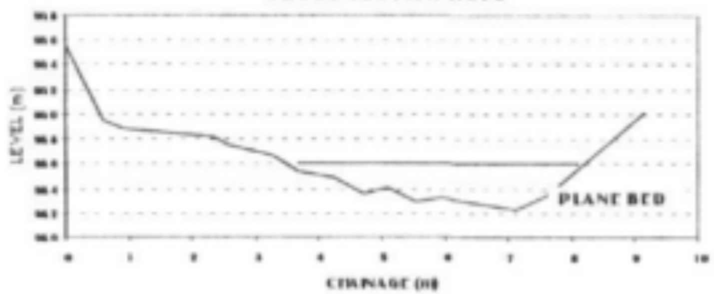
CROSS SECTION NO. 2



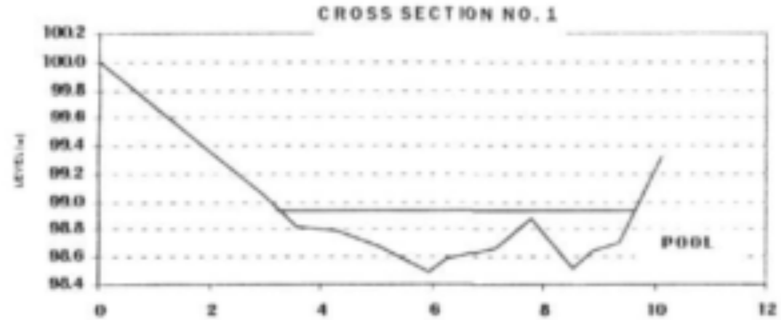
CROSS SECTION NO. 5

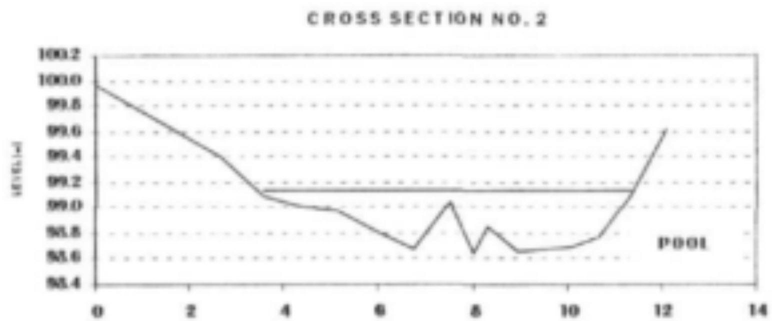


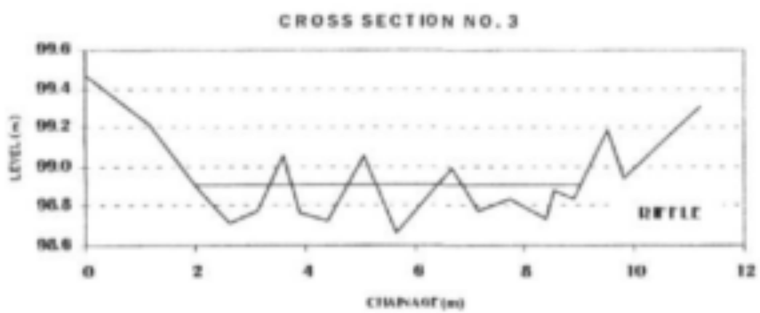
CROSS SECTION NO. 3

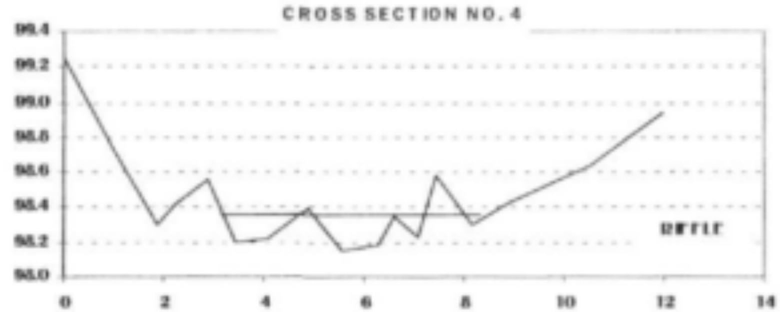


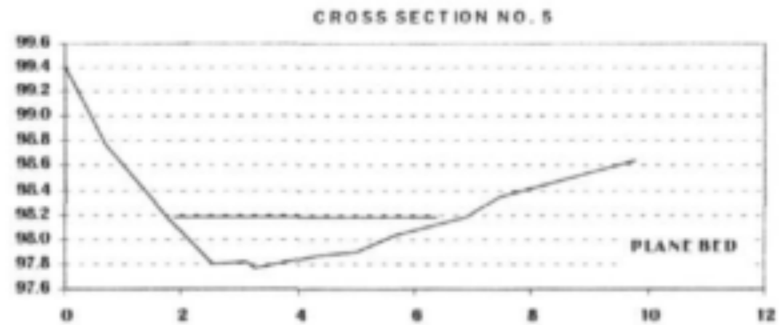
Vergenoeg

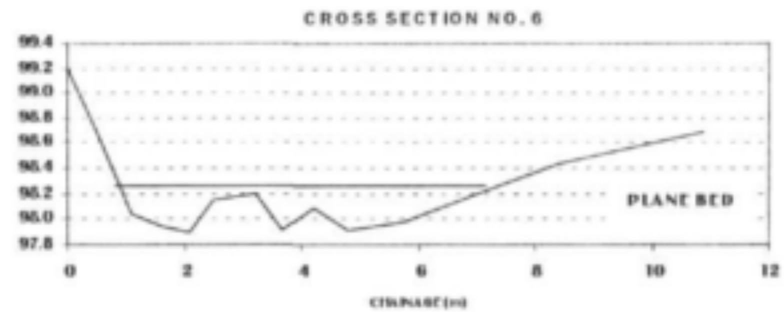

CROSS SECTION NO. 1
LEVEL (m)
POOL


CROSS SECTION NO. 2
LEVEL (m)
POOL


CROSS SECTION NO. 3
LEVEL (m)
RIFFLE
CHAINAGE (m)

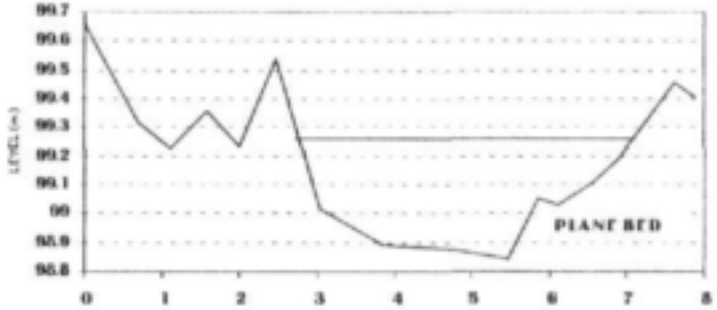

CROSS SECTION NO. 4
RIFFLE


CROSS SECTION NO. 5
PLANE BED

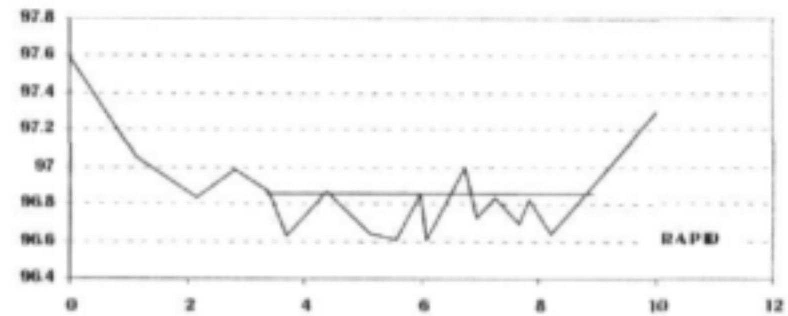

CROSS SECTION NO. 6
PLANE BED
CHAINAGE (m)

Berg 1

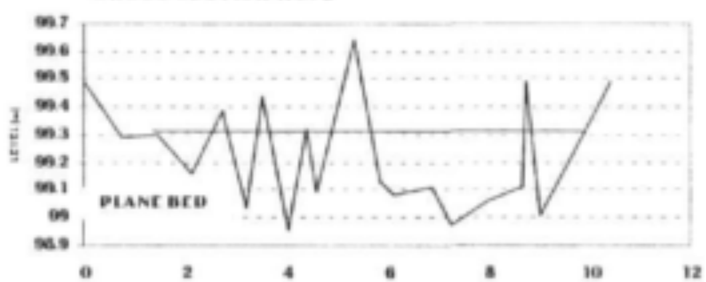
CROSS SECTION NO. 1



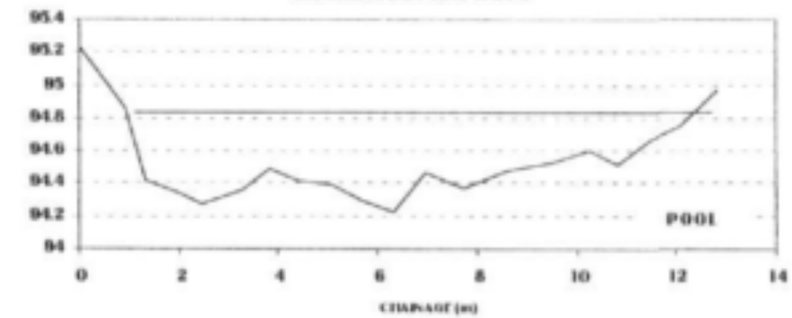
CROSS SECTION NO. 4



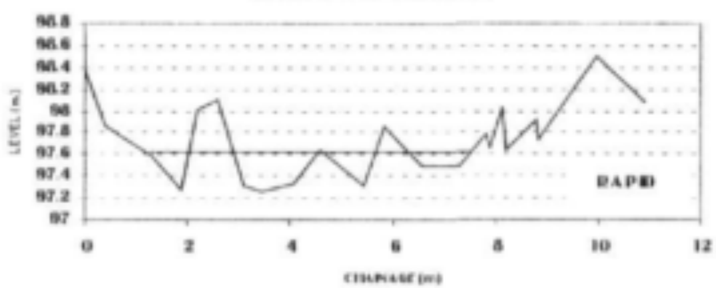
CROSS SECTION NO. 2



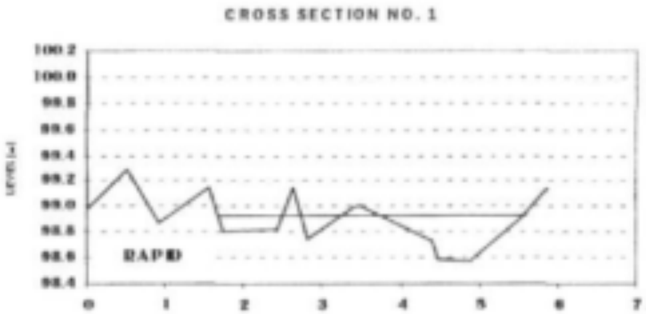
CROSS SECTION NO. 5

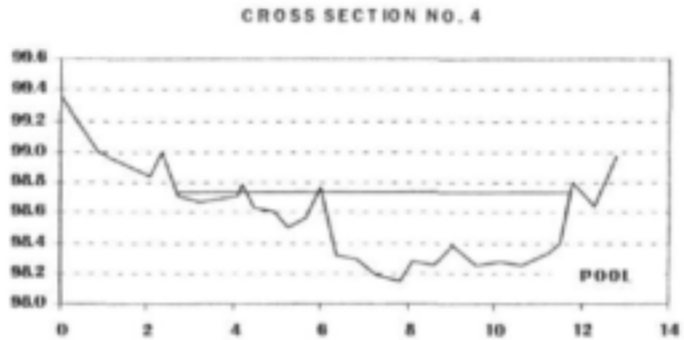


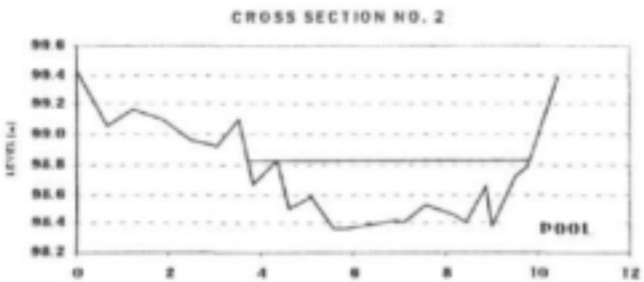
CROSS SECTION NO. 3

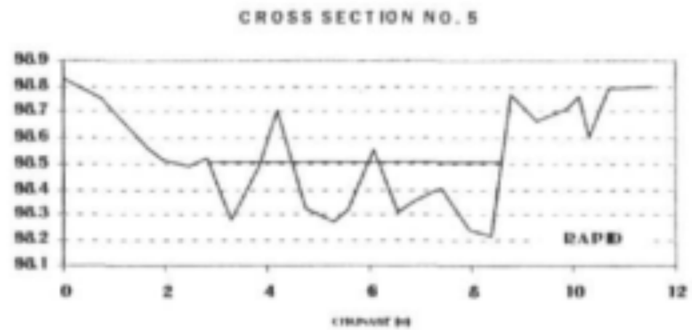


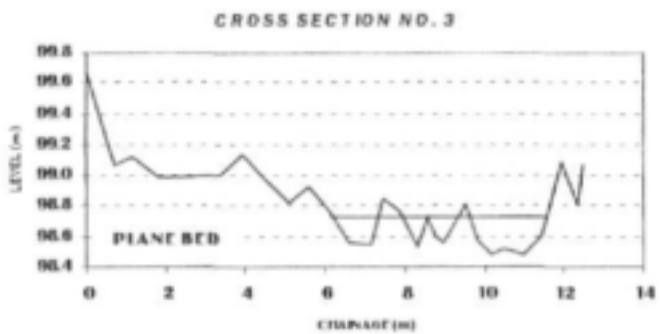
Berg 2


CROSS SECTION NO. 1
LEVEL (m)
RAPID


CROSS SECTION NO. 4
POOL

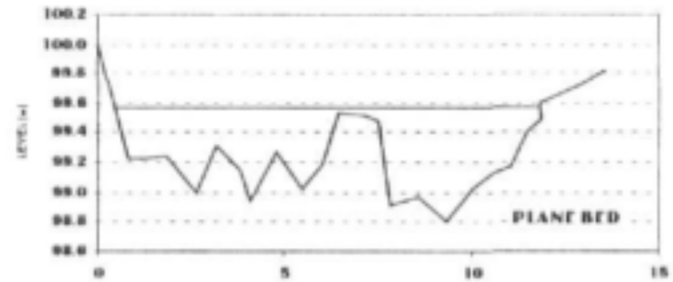

CROSS SECTION NO. 2
LEVEL (m)
POOL


CROSS SECTION NO. 5
RAPID

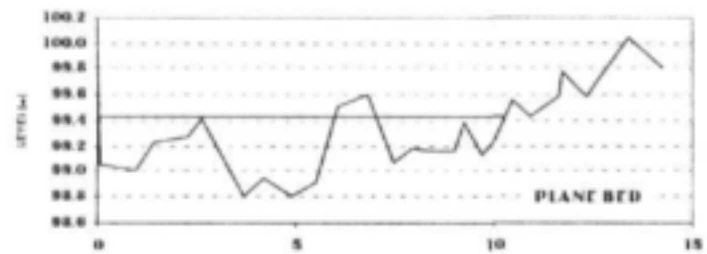

CROSS SECTION NO. 3
LEVEL (m)
PLANE BED
CHAINAGE (m)

Elands

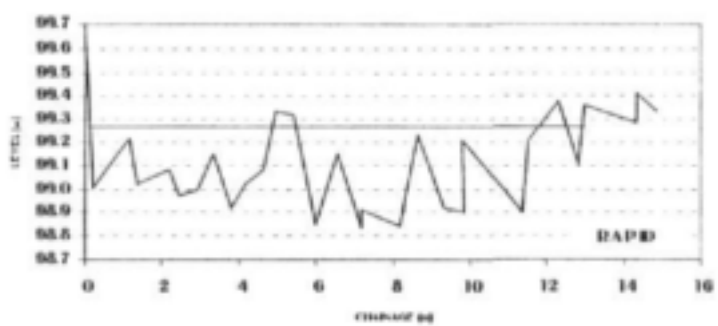
CROSS SECTION NO. 1



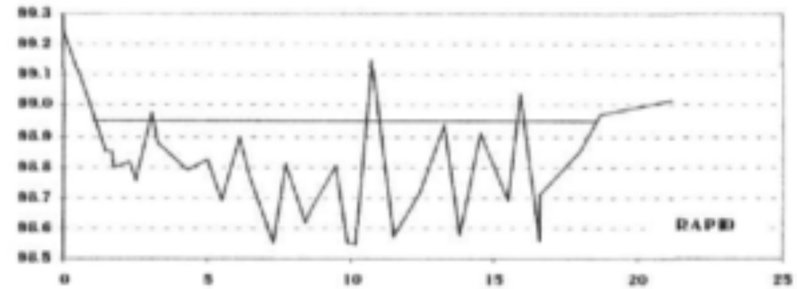
CROSS SECTION NO. 2



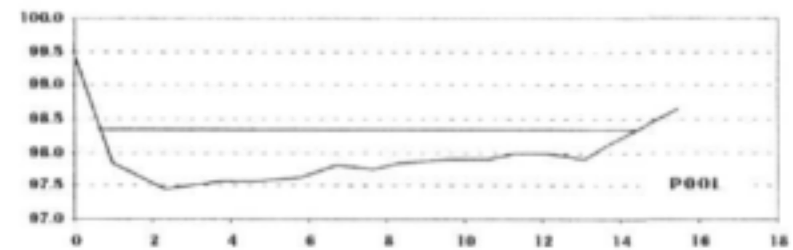
CROSS SECTION NO. 3



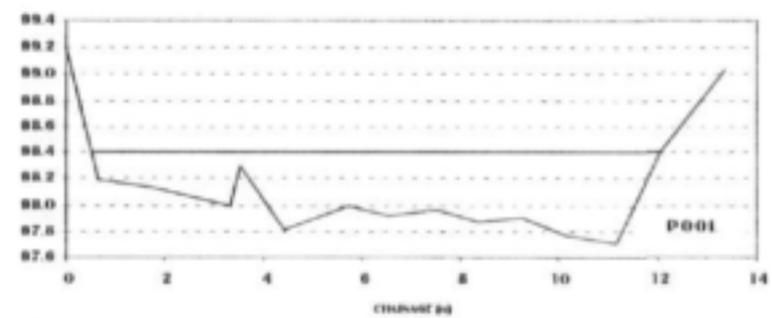
CROSS SECTION NO. 4



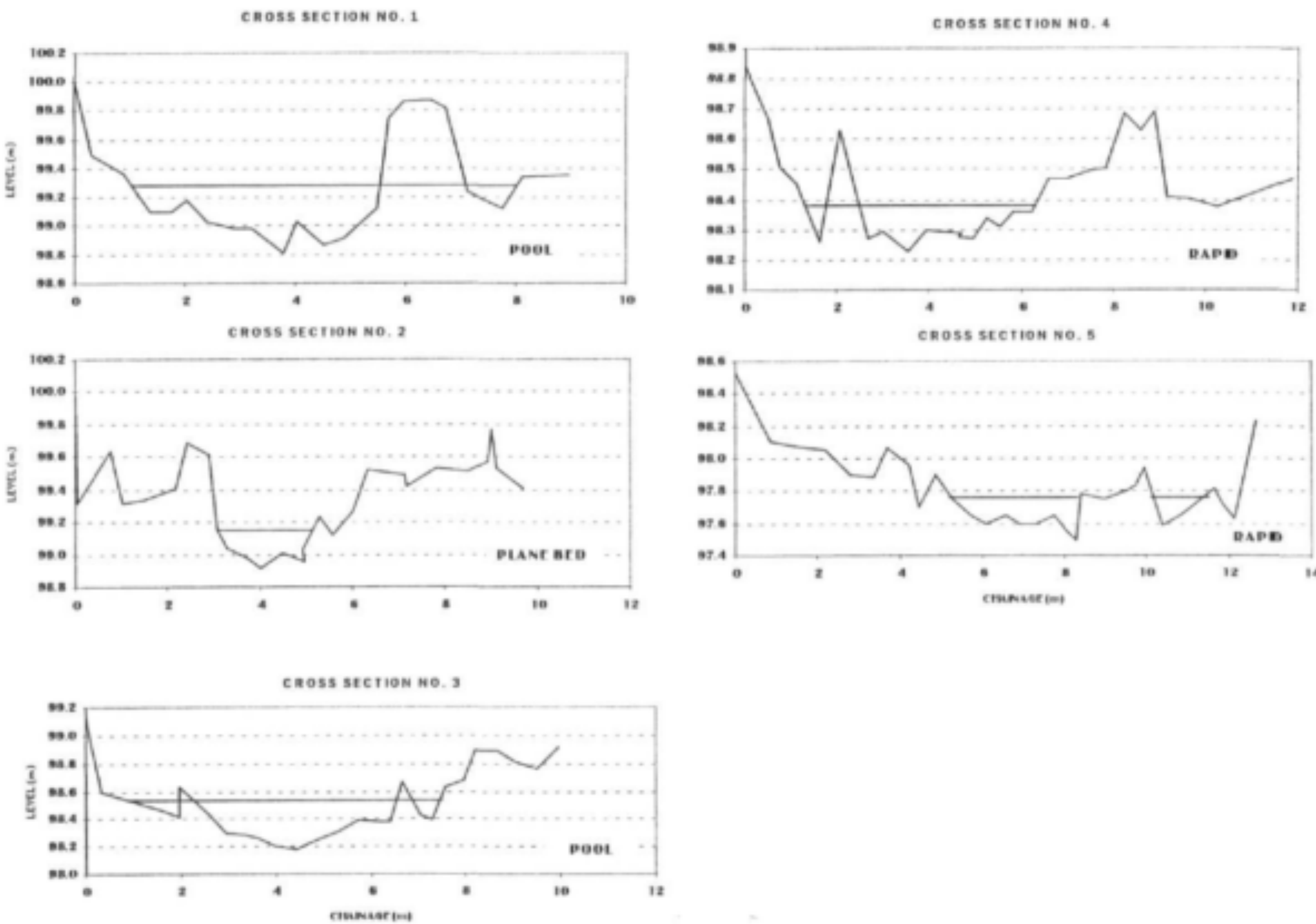
CROSS SECTION NO. 5



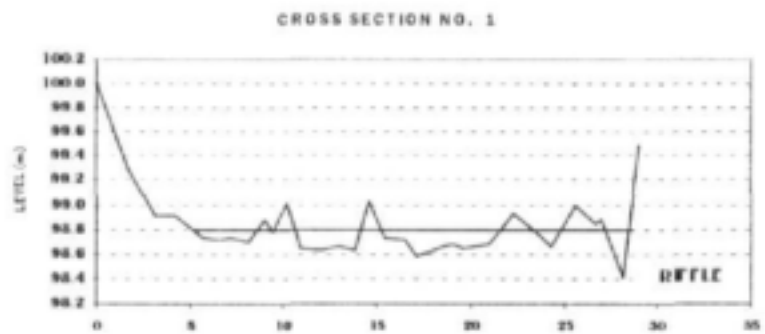
CROSS SECTION NO. 6

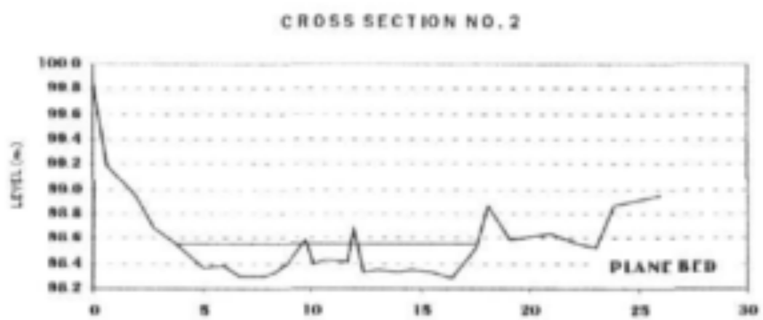


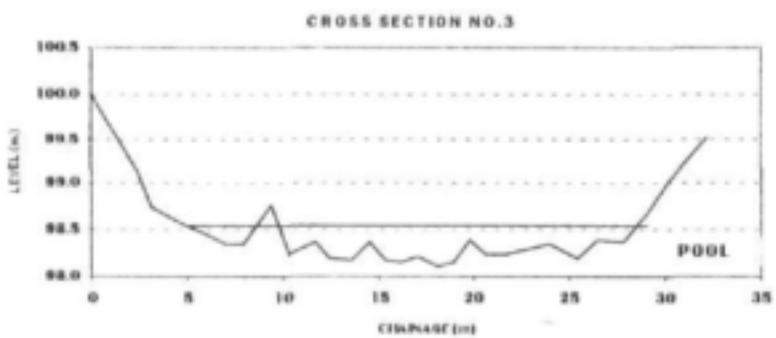
Du Toits


CROSS SECTION NO. 1
POOL
CROSS SECTION NO. 2
PLANE BED
CROSS SECTION NO. 3
POOL
CROSS SECTION NO. 4
RAPID
CROSS SECTION NO. 5
RAPID
LEVEL (m)
CHAINAGE (m)

Molenaars 1

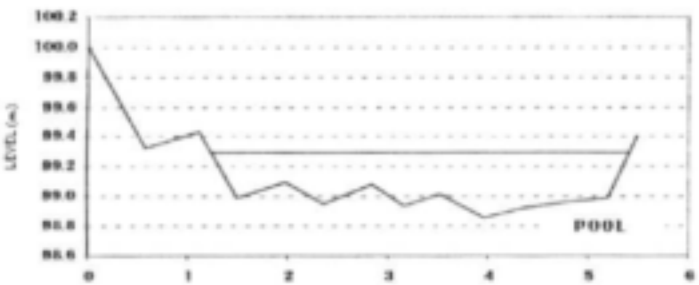

CROSS SECTION NO. 1
100.2
100.0
99.8
99.6
99.4
99.2
99.0
98.8
98.6
98.4
98.2
LEVEL (m)
RIFFLE
0
5
10
15
20
25
30
35


CROSS SECTION NO. 2
100.0
99.8
99.6
99.4
99.2
99.0
98.8
98.6
98.4
98.2
LEVEL (m)
PLANE BED
0
5
10
15
20
25
30

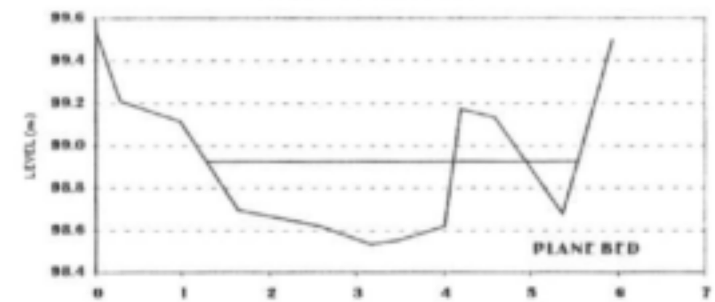

CROSS SECTION NO.3
100.5
100.0
99.5
99.0
98.5
98.0
LEVEL (m)
POOL
0
5
10
15
20
25
30
35
CHAINAGE (m)

Jonkershoek

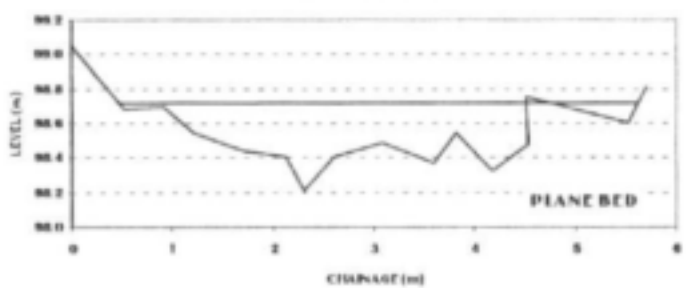
CROSS SECTION NO. 1



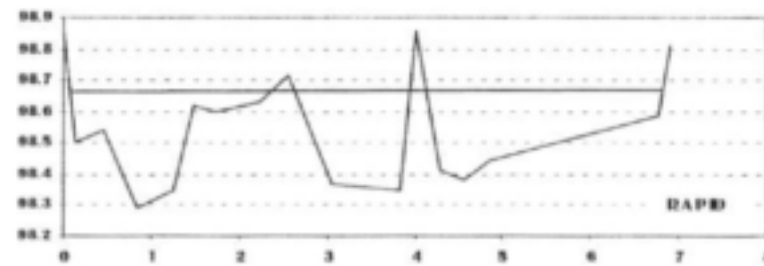
CROSS SECTION NO. 2



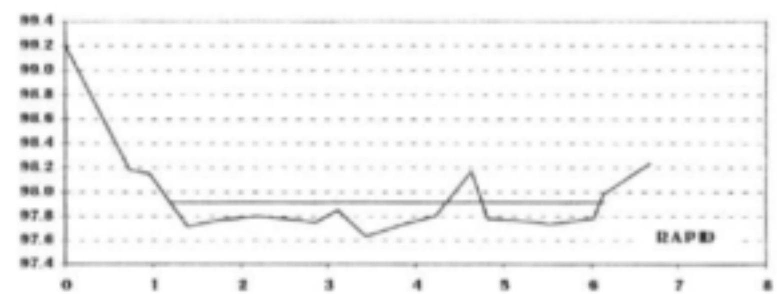
CROSS SECTION NO. 3



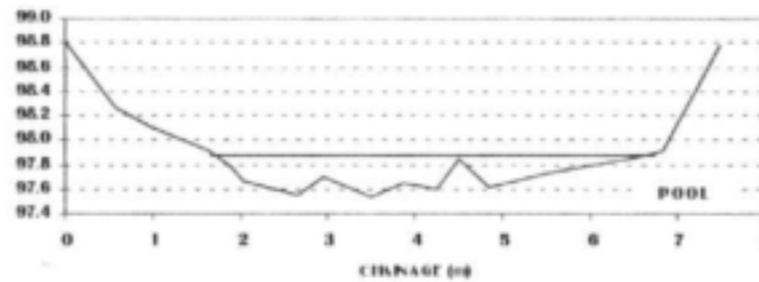
CROSS SECTION NO. 4



CROSS SECTION NO. 5

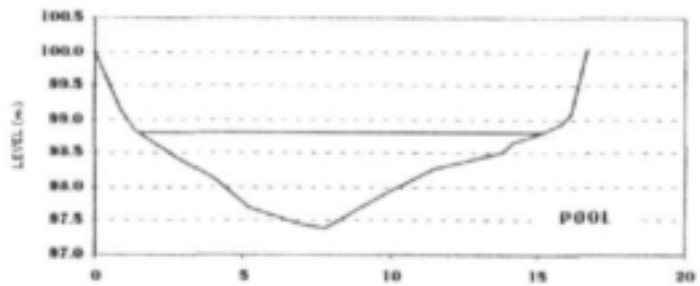


CROSS SECTION NO. 6

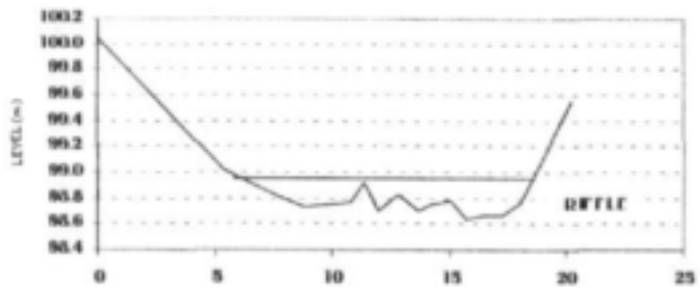


Vlottenburg

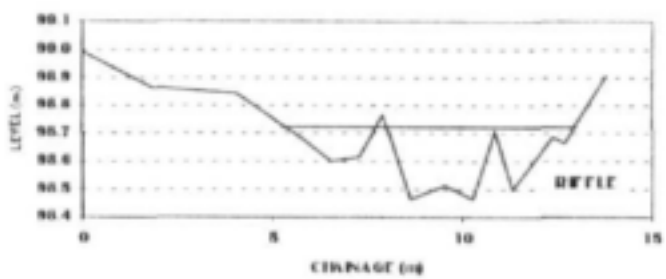
CROSS SECTION NO. 1



CROSS SECTION NO. 2



CROSS SECTION NO. 3



APPENDIX I : *Hydraulic and biotope data

Discharge information

Site	**Discharge (m^3/s)**
Whitebridge	0.085
Jonkershoek	0.132
Vergenoeg	0.134
Vlottenburg	0.903
Elands	0.577
Molenaars	0.468
Berg1	0.094
Berg2	0.140
DuToits	0.034

*Corresponding water levels indicated in Appx. H

DU TOITS

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

Cross section : 1 — Morphological Unit : Pool

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	280	0.01	b	bpf
2	420	0.03	c	bpf
3	480	0.03	b	bpf
4	330	0.02	g	bpf
5	190	0	g	nf
6	370	0.04	b	bpf
7	430	0.09	c	sbt
8	380	0.1	b	sbt
9	270	0.03	b	sbt
10	230	0.01	b	bpf
11	320	0.07	b	sbt
12	340	0.03	b	bpf
13	370	0.05	c	sbt
14	420	0.08	g	sbt
15	290	0.06	b	sbt

Cross section : 2 — Morphological Unit : Plane bed

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	240	0.06	b	sbt
2	210	0.17	c	rs
3	190	0.14	c	rs
4	190	0.12	c	rs
5	130	0.19	c	sbt
6	300	0.06	b	sbt
7	220	0.16	c	rs
8	100	0.12	b	rs
9	170	0.07	c	rs
10	180	0.29	c	bsw
11	160	0.31	c	bsw
12	220	0.06	c	rs
13	230	0.08	b	rs
14	250	0.06	g	sbt
15	200	0.03	b	sbt

Cross section : 5 — Morphological Unit : Rapid

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	60	0.02	g	usw
2	50	0.29	c	rs
3	150	0.43	c	rs
4	120	0.28	c	bsw
5	170	0.32	c	rs
6	80	0.39	c	bpf
7	160	0.29	c	usw
8	200	0.03	c	rs
9	50	0.32	c	sbt
10	180	0.15	c	bsw
11	120	0.53	c	usw
12	70	0.8	c	rs
13	100	0.39	b	rs
14	150	0.05	c	usw
15	110	0.05	g	rs
16	140	0.47	c	rs
17	70	0.21	c	usw
18	130	0.16	b	bpf
19	130	0.26	c	sbt
20	100	0.03	g	rs
21	160	0.08	c	usw
22	160	0.17	c	usw
23	100	0.49	c	rs
24	110	0.57	c	usw
25	70	0.09	c	usw
26	60	0.49	c	rs
27	90	0.44	c	sbt
28	190	0.35	c	rs
29	90	0.03	c	
30	120	0.1	c	

Cross section : 3 — Morphological Unit : Pool

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	120	0.05	c	sbt
2	240	0.05	c	bpf
3	200	0.09	c	sbt
4	100	0.03	b	bpf
5	170	0.01	b	bpf
6	240	0.12	c	sbt
7	260	0.13	b	sbt
8	160	0.14	c	sbt
9	260	0.2	b	rs
10	280	0.23	c	rs
11	260	0.05	c	rs
12	160	0.02	b	bpf
13	400	0.01	c	bpf
14	330	0.02	c	bpf
15	210	0.06	g	sbt

Cross section : 4 — Morphological Unit : Rapid

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	60	0.45	b	sbt
2	120	0.46	c	usw
3	110	0.51	c	usw
4	130	0.29	c	rs
5	140	0.69	b	sbt
6	150	0.66	b	usw
7	90	0.09	g	rs
8	50	0.32	c	usw
9	170	0.01	s	bpf
10	90	0.27	c	usw
11	110	0.23	g	rs
12	120	0.1	c	rs
13	100	0.55	b	sbt
14	220	0.2	c	rs
15	150	0.49	c	usw

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

Cross section : 1 — Morphological Unit : Pool

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	180	0.05	g	bpf
2	200	0.01	g	bpf
3	230	0.06	b	bpf
4	320	0.09	b	sbt
5	220	0.04	b	bpf
6	340	0.01	b	bpf
7	250	0	c	nf
8	140	0	g	nf

Cross section : 2 — Morphological Unit : Plane bed

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	150	0.12	c	rs
2	200	0.04	c	rs
3	250	0.17	c	rs
4	160	0.09	b	rs
5	230	0.02	g	bpf
6	160	0.02	c	sbt
7	120	0.14	c	usw
8	50	0.44	b	sbt

Cross section : 3 — Morphological Unit : Pool

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
	180	0.07	c	bpf
	180	0.11	c	sbt
	180	0.11	c	sbt
	280	0.06	c	sbt
	360	0.01	c	bpf
	250	0.01	c	bpf
	120	0.01	g	bpf
	130	0.01	g	bpf
	90	0.01	g	bpf

Cross section : 4 — Morphological Unit : Rapid

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	140	0	g	nf
2	80	0.13	c	rs
3	100	0.16	g	rs
4	100	0.14	g	rs
5	100	0.33	c	usw
6	90	0.18	c	usw
7	100	0.13	g	rs
8	140	0.14	c	rs
9	90	0.09	c	rs

Cross section : 5 — Morphological Unit : Rapid

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	50	0.02	c	bpf
2	120	0.06	c	sbt
3	140	0.11	c	rs
4	90	0.09	b	sbt
5	160	0.19	c	rs
6	50	0.26	c	srf
7	50	0.02	c	rs
8	60	0.09	b	rs
9	70	0.13	g	rs

MOLENAARS I

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

	Cross section :		3		Cross section :		2		Cross section :		1	
	Morphological Unit :		Pool		Morphological Unit :		Plane bed		Morphological Unit :		Riffle	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	180	0.01	g	bpf	200	0.15	g	rs	100	0.1	g	rs
2	300	0.08	c	sbt	220	0.21	c	rs	180	0.42	c	rs
3	240	0.09	c	sbt	220	0.19	c	rs	200	0.4	c	usw
4	140	0.13	b	sbt	180	0.19	b	rs	200	0.5	c	bsw
5	220	0.18	c	sbt	320	0.23	g	rs	180	0.4	c	usw
6	300	0.21	c	sbt	280	0.14	c	rs	200	0.58	c	bsw
7	330	0.15	b	sbt	240	0.05	b	rs	240	0.31	b	usw
8	320	0.09	g	sbt	220	0.29	c	rs	180	0.21	c	rs
9	300	0.15	b	sbt	240	0.04	b	bpf	200	1.01	c	bsw
10	140	0.03	c	bpf	200	0.08	g	sbt	200	0.15	s	rs
11	100	0.01	c	bpf	260	0.07	g	sbt	110	0.82	c	bsw
12	380	0.04	c	bpf	260	0.17	b	sbt	70	0.27	c	usw
13	180	0.08	b	sbt	380	0.16	g	rs	100	0.65	c	usw
14	370	0.11	g	sbt	250	0.12	c	rs	150	0.78	c	usw
15	380	0.1	c	sbt	260	0.24	c	rs	90	0.61	c	usw
16	300	0.15	b	sbt	200	0.3	b	sbt	160	0.68	c	bsw
17	360	0.18	c	sbt	250	0.1	c	rs	80	0.31	c	srf
18	400	0.11	g	sbt	220	0.31	c	rs	210	0.68	c	sbt
19	360	0.1	c	sbt	280	0.26	c	rs	260	0.04	s	rs
20	280	0.09	b	sbt	220	0.28	b	rs	200	0.52	g	rs
21	320	0.09	c	sbt	120	0.06	s	bpf	90	0.27	c	usw
22	200	0.06	g	sbt	240	0.19	g	sbt	200	0.32	c	usw
23	170	0.02	g	bpf	350	0.26	c	rs	180	0.18	c	usw
24	220	0.05	c	bpf	220	0.08	b	sbt	230	0.38	c	usw
25	300	0.06	c	bpf	330	0.16	c	rs	120	0.57	c	bsw
26	360	0.12	c	sbt	310	0.15	c	sbt	220	0.16	s	rs
27	280	0.13	b	sbt	280	0.31	c	rs	110	0.33	c	usw
28	460	0.14	g	sbt	200	0.14	c	rs	120	0.22	b	rs
29	360	0.14	c	sbt	190	0.39	c	rs	140	0.19	c	rs
30	300	0.1	c	sbt	220	0.36	c	rs	190	0.1	b	sbt

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

	Cross section :		1		Cross section :		2		Cross section :		3	
	Morphological Unit :		Riffle		Morphological Unit :		Plane bed		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	100	0.12	c	rs	220	0.04	g	bpf	80	0.03	c	bpf
2	100	0.3	c	usw	160	0.12	b	rs	180	0.03	g	bpf
3	60	0.07	c	sbt	300	0.06	c	sbt	280	0.03	g	bpf
4	80	0.28	c	usw	260	0.23	b	rs	170	0.12	b	sbt
5	100	0.24	c	bsw	180	0.15	c	rs	200	0.16	c	sbt
6	80	0.19	g	usw	150	0.28	c	rs	290	0.08	c	sbt
7	120	0.54	c	usw	150	0.28	c	rs	260	0.07	g	sbt
8	60	0.21	c	rs	200	0.23	c	rs	300	0.1	c	sbt
9	110	0.33	c	rs	320	0.25	c	rs	370	0.11	c	sbt
10	220	0.37	c	sbt	230	0.32	c	rs	260	0.16	b	sbt
11	200	0.56	c	bsw	280	0.16	s	rs	470	0.15	c	sbt
12	120	0.29	c	usw	120	0.13	c	sbt	260	0.14	c	sbt
13	160	0.33	c	usw	90	0.03	c	bpf	290	0.11	c	sbt
14	200	0.44	c	usw	100	0.02	s	bpf	250	0.1	c	sbt
15	120	0.53	g	usw					240	0.09	c	sbt
16	180	0.76	c	sbt					300	0.05	c	bpf
17	120	0.12	c	rs					280	0.04	b	bpf
18	100	0.01	s	bpf					170	0.06	c	bpf

VLOTTENBURG

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

	Cross section : 3 & 4 Morphological Unit : Riffle				Cross section : 1 Morphological Unit : Pool			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	145	0.08	c	sbt	350	0.1	c	bpf
2	250	0.45	c	usw	480	0.12	c	bpf
3	250	0.6	c	usw	350	0.13	b	bpf
4	100	0.06	c	rs	340	0.11	c	bpf
5	110	0.06	g	rs	360	0.09	c	bpf
6	230	0.27	c	usw	330	0.07	c	bpf
7	140	0.56	c	usw	220	0.05	c	bpf
8	120	0.55	c	bsw	240	0.1	c	bpf
9	180	0.64	c	bsw	630	0.05	c	bpf
10	170	0.62	c	usw	800	0.06	c	bpf
11	100	0.5	c	usw	1010	0.1	c	bpf
12	120	0.41	c	bsw	1000	0.09	c	bpf
13	120	0.05	g	rs	840	0.1	b	bpf
14	110	0.34	c	usw	1120	0.08	c	bpf
15	210	0.6	c	usw	860	0.09	b	bpf
16	220	0.36	c	usw	790	0.06	c	bpf
17	160	0.13	c	rs	680	0.04	g	bpf
18	120	0.11	c	rs	660	0.05	g	bpf
19	220	0.32	c	rs	680	0.04	g	bpf
20	220	0.57	c	usw	800	0.02	s	bpf
21	200	0.21	c	rs	740	0.01	s	bpf
22	160	0.43	c	usw	1000	0.01	s	bpf
23	160	0.35	c	usw	1080	0.01	s	bpf
24	120	0.6	c	bsw	1160	0.01	s	bpf
25	140	0.47	c	usw	1200	0.01	c	bpf
26	140	0.34	c	rs	1100	0.02	b	bpf
27	60	0.24	c	usw	1100	0.05	c	bpf
28	70	0.18	c	usw	1020	0.07	b	bpf
29	180	0.15	c	usw	920	0.1	c	bpf
30	160	0.33	c	usw	740	0.08	c	bpf

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

	Cross section : 1 Morphological Unit : Pool				Cross section : 3 Morphological Unit : Riffle			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	1100	0.08	s	bpf	120	0.37	c	usw
2	1100	0.07	s	bpf	100	0.23	c	rs
3	800	0.07	s	bpf	160	0.3	c	usw
4	650	0.01	s	bpf	100	0.7	c	usw
5	540	0.06	s	bpf	100	0.28	c	usw
6	380	0.03	s	bpf	120	0.51	c	usw
7	420	0.13	c	bpf	150	0.32	c	usw
8					180	0.64	c	usw
9					180	0.31	c	rs

	Cross section : 4 Morphological Unit : Riffle			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	140	0.44	c	rs
2	120	0.52	c	usw
3	80	0.25	c	bsw
4	140	0.7	c	bsw
5	260	0.34	c	usw
6	220	0.6	c	usw
7	200	0.6	c	usw
8	240	0.56	c	bsw
9	200	0.42	c	usw
10	200	0.47	c	rs

JONKERSHOEK

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

	Cross section :		1		Cross section :		2		Cross section :		3	
	Morphological Unit :		Pool		Morphological Unit :		Plane bed		Morphological Unit :		Plane bed	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	360	0.09	b	bpf	220	0.01	c	sbt	320	0.08	c	sbt
2	340	0.11	c	sbt	220	0.06	b	rs	300	0.26	b	rs
3	270	0.13	b	sbt	380	0.45	c	usw	380	0.18	b	rs
4	60	0.15	b	sbt	320	0.52	b	usw	360	0.16	c	rs
5	320	0.16	b	rs	300	0.17	c	rs	440	0.1	b	rs
6	360	0.2	c	sbt	200	0.02	g	bpf	430	0.23	b	rs
7	340	0.09	s	bpf	230	0.16	b	rs	140	0.21	b	rs
8	60	0.04	b	sbt	300	0.4	c	rs	180	0.11	c	usw
9	220	0.04	c	bpf	120	0.52	b	rs	350	0.23	c	rs
10	300	0.05	b	bpf	180	0.19	c	rs	100	0.26	g	rs
11	120	0.04	g	bpf	210	0.08	c	rs	110	0.09	c	sbt
12	300	0.13	b	sbt	160	0.03	s	bpf	320	0.38	b	usw
13	400	0.1	c	sbt	160	0.04	c	bpf	600	0.01	c	bpf
14	380	0.1	c	sbt	100	0.04	b	sbt	400	0.16	c	rs
15	500	0.18	c	rs	120	0.16	b	rs	480	0.11	c	rs

	Cross section :		4		Cross section :		5		Cross section :		6	
	Morphological Unit :		Rapid		Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	140	0.02	b	sbt	130	0.03	b	rs	130	0.04	b	bpf
2	300	0.45	c	usw	300	0.1	b	usw	150	0.14	b	sbt
3	300	0.3	c	rs	380	0.24	b	usw	280	0.24	g	sbt
4	180	0.87	b	sbt	340	0.03	c	rs	220	0.07	c	sbt
5	190	0.62	c	bsw	240	0.56	b	bsw	320	0.1	c	sbt
6	200	0.05	c	sbt	140	0.99	b	sbt	140	0.07	b	bpf
7	180	0.32	c	sbt	180	0.77	c	bsw	150	0.02	s	bpf
8	180	0.03	c	bpf	160	0.83	c	usw	280	0.2	g	sbt
9	200	0.38	c	bsw	110	0.71	c	usw	280	0.04	b	sbt
10	190	0.81	b	sbt	120	0.65	b	bsw	310	0.18	c	sbt
11	250	0.39	b	bsw	120	1.55	b	bsw	300	0.16	c	rs
12	320	0.34	b	bsw	100	1.15	b	sbt	420	0.18	b	rs
13	120	0.71	b	sbt	220	0.43	b	rs	350	0.04	s	sbt
14					140	0.21	c	usw	400	0.12	c	sbt
15					260	0.35	c	rs	340	0.03	c	bpf

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

	Cross section :		1		Cross section :		2		Cross section :		3	
	Morphological Unit :		Pool		Morphological Unit :		Plane bed		Morphological Unit :		Plane bed	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	360	0.08	s	bpf	180	0.04	c	sbt	100	0.02	s	bpf
2	240	0.07	c	bpf	220	0.03	s	rs	160	0.05	s	bpf
3	280	0.04	c	bpf	220	0.48	b	rs	300	0.03	s	bpf
4	280	0.07	b	bpf	360	0.35	c	rs	400	0.15	b	rs
5	320	0.13	b	sbt	230	0.11	c	rs	460	0.26	b	rs
6	480	0.12	c	sbt	100	0.01	b	bpf	320	0.13	b	sbt
7	420	0.09	b	sbt					400	0.06	c	sbt
8	320	0.11	b	sbt					200	0.04	c	bpf
9	220	0.06	b	bpf					80	0.13	c	sbt

	Cross section :		4		Cross section :		5		Cross section :		6	
	Morphological Unit :		Rapid		Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	160	0.05	c	rs	230	0.71	c	bsw	90	0.01	s	bpf
2	300	0.2	c	rs	150	1.07	c	bsw	310	0.02	c	bpf
3	120	0.22	b	bsw	180	0.68	b	bsw	300	0.04	b	sbt
4	220	0.13	c	usw	130	0.07	b	usw	390	0.04	c	sbt
5	220	0.58	b	usw	180	0.11	b	usw	340	0.11	b	rs
6	200	0.1	c	usw	180	0.06	g	rs	350	0.11	c	rs
7	210	0.21	c	rs	140	0.03	b	bpf	310	0.14	g	rs
8	120	0.05	b	sbt					150	0.02	b	bpf
9	80	0.02	s	bpf					140	0.01	c	bpf

WHITEBRIDGE

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

	Cross section :		4		Cross section :		6	
	Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	380	0.1	c	rs	180	0.13	b	bpf
2	220	0.7	g	usw	330	0.16	b	bpf
3	100	1.06	b	bsw	80	0.05	c	bpf
4	160	0.99	c	sbt	380	0.18	c	sbt
5	240	0.38	b	bsw	320	0.04	b	bpf
6	80	0.05	g	bpf	320	0.11	s	sbt
7	120	0.7	b	rs	130	0.23	b	rs
8	260	0.21	b	usw	340	0.09	g	sbt
9	300	0.51	b	bsw	450	0.1	c	sbt
10	160	0.05	b	rs	160	0.08	c	bpf
11	260	0.73	c	usw	380	0.09	s	bpf
12	200	0.63	c	usw	280	0.13	b	bpf
13	100	0.05	g	bpf	160	0.05	g	bpf
14	50	0.56	c	sbt	360	0.11	c	sbt
15	140	0.77	b	sbt	80	0.15	c	sbt

	Cross section :		3		Cross section :		1		Cross section :		2	
	Morphological Unit :		Plane bed		Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	200	0.28	c	rs	120	0.62	b	sbt	480	0.03	b	bpf
2	200	0.2	b	rs	140	0.4	c	rs	450	0.04	b	bpf
3	120	0.21	c	rs	140	0.51	c	usw	280	0.04	c	sbt
4	190	0.19	c	rs	160	0.3	c	rs	200	0.03	g	sbt
5	140	0.12	g	sbt	120	0.05	g	rs	340	0.1	b	rs
6	120	0.15	g	rs	120	0.19	c	bsw	420	0.13	c	rs
7	140	0.1	b	rs	160	0.25	c	bsw	480	0.09	c	rs
8	140	0.41	b	bsw	100	0.71	b	bsw	260	0.02	c	bpf
9	80	0.12	b	rs	140	0.25	c	usw	380	0.09	g	sbt
10	160	0.08	b	rs	200	0.48	c	usw	80	0.08	b	sbt
11	200	0.16	c	rs	120	0.03	c	sbt	150	0.12	b	sbt
12	190	0.45	c	bsw	200	0.82	b	sbt	220	0.12	c	sbt
13	120	0.22	b	rs	180	1.54	b	bsw	280	0.1	b	sbt
14	130	0.24	c	rs	190	0.39	c	usw	250	0.03	c	bpf
15	200	0.41	c	bsw	100	0.95	c	usw	200	0.03	g	rs

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

	Cross section :		4		Cross section :		6	
	Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	160	1.14	b	sbt	50	0.03	c	bpf
2	80	0.49	c	bsw	60	0.06	b	bpf
3	60	0.11	c	rs	200	0.08	c	bpf
4	50	0.09	g	rs	180	0.2	b	sbt
5					300	0.11	c	rs
6					340	0.06	s	bpf
7					320	0.04	b	bpf
					380	0.06	s	bpf

	Cross section :		3		Cross section :		1		Cross section :		2	
	Morphological Unit :		Plane bed		Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	140	0.23	c	rs	50	0.02	c	rs	410	0.07	b	bpf
2	70	0.47	b	bsw	150	0.19	c	rs	320	0.1	b	bpf
3	100	0.18	b	rs	160	0.37	c	rs	380	0.09	b	sbt
4	180	0.1	b	rs	100	0.28	b	rs	180	0.04	g	bpf
5	200	0.06	b	rs	160	0.58	b	sbt	190	0.04	g	bpf
6	210	0.08	g	rs					200	0.07	c	sbt
7	170	0.27	g	rs					300	0.12	b	sbt
8									350	0.11	b	rs
9									380	0.12	c	rs
10									380	0.04	s	bpf

VERGENDEG

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

Cross section : 5 & 6 — Morphological Unit : Plane bed

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	80	0.13	c	sbt
2	200	0.1	c	rs
3	260	0.3	b	rs
4	80	0.13	b	rs
5	280	0.25	c	rs
6	200	0.15	c	rs
7	360	0.1	c	rs
8	250	0.09	c	rs
9	110	0.03	g	bpf
10	200	0.15	c	sbt
11	160	0.26	b	rs
12	300	0.19	c	rs
13	340	0.17	b	sbt
14	320	0.18	c	sbt
15	330	0.23	c	rs
16	120	0.22	b	sbt
17	100	0.04	c	bpf
18	190	0.26	c	rs
19	300	0.16	c	sbt
20	170	0.17	b	sbt
21	390	0.16	c	rs
22	280	0.11	c	rs
23	140	0.21	b	rs
24	340	0.23	c	rs
25	150	0.23	b	rs
26	260	0.26	c	rs
27	250	0.24	c	rs
28	240	0.14	c	sbt
29	160	0.21	b	rs
30	260	0.04	b	bpf

Cross section : 3 — Morphological Unit : Riffle

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	120	0.34	c	bsw
2	150	0.25	c	usw
3	160	0.85	c	sbt
4	140	0.41	c	bsw
5	90	0.5	b	bsw
6	140	0.45	c	usw
7	60	0.51	c	bsw
8	90	0.12	b	rs
9	80	0.02	c	bpf
10	90	0.3	c	usw
11	160	0.53	c	usw
12	200	0.64	c	usw
13	120	0.42	b	usw
14	80	0.62	b	usw
15	160	0.52	c	bsw

Cross section : 4 — Morphological Unit : Riffle

Depth (mm)	Velocity (m/s)	Substrate	Flow Type
170	0.25	c	usw
200	0.98	b	sbt
120	0.34	c	bsw
150	0.43	c	usw
200	0.31	c	usw
100	0.13	c	rs
60	0.06	c	bpf
220	0.49	c	bsw
200	0.69	b	sbt
180	0.87	b	bsw
260	0.1	b	rs
280	0.23	c	usw
200	0.38	c	usw
160	0.33	c	bsw
120	0.51	b	sbt

Cross section : 1 & 2 — Morphological Unit : Pool

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	300	0.07	c	bpf
2	300	0.1	b	bpf
3	200	0.1	b	sbt
4	160	0.14	b	sbt
5	240	0.08	c	sbt
6	410	0.09	c	sbt
7	240	0.13	c	sbt
8	290	0.08	c	bpf
9	100	0.07	c	bpf
10	160	0.05	s	bpf
11	570	0.13	c	sbt
12	540	0.05	c	bpf
13	500	0.14	b	sbt
14	620	0.1	c	bpf
15	110	0.02	s	bpf
16	360	0.04	v	bpf
17	460	0.03	g	bpf
18	280	0.07	b	sbt
19	360	0.05	c	bpf
20	210	0.03	s	bpf
21	640	0.12	b	sbt
22	440	0.04	c	bpf
23	230	0.04	g	bpf
24	280	0.05	b	bpf
25	420	0.03	c	bpf
26	360	0.05	c	bpf
27	350	0.09	b	sbt
28	450	0.1	c	sbt
29	280	0.15	b	sbt
30	600	0.11	c	sbt

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

Cross section : 1 — Morphological Unit : Pool

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	220	0.03	s	bpf
2	300	0.02	c	bpf
3	330	0.03	c	bpf
4	400	0.06	b	bpf
5	500	0.06	c	sbt
6	540	0.1	b	sbt
7	620	0.08	b	sbt
8	350	0.21	b	sbt
9	530	0.08	b	bpf
10	460	0.05	c	bpf

Cross section : 2 — Morphological Unit : Pool

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	50	0.03	c	bpf
2	150	0.07	c	bpf
3	170	0.06	c	bpf
4	300	0.08	c	bpf
5	380	0.13	b	sbt
6	100	0.12	b	sbt
7	470	0.08	b	sbt
8	390	0.1	b	sbt
9	340	0.12	c	bpf
10	380	0.07	c	bpf
	300	0.04	s	bpf

Cross section : 3 — Morphological Unit : Riffle

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	80	0.28	c	usw
2	60	0.24	c	sbt
3	100	0.23	c	bsw
4	200	0.54	b	bsw
5	110	0.7	b	sbt
6	100	0.63	c	bsw
7	100	0.24	c	bsw
8	140	0.41	c	usw

Cross section : 4 — Morphological Unit : Riffle

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	70	0.09	c	srf
2	180	0.43	c	bsw
3	200	0.26	c	rs
4	170	0.29	c	usw
5	120	0.29	c	bsw
6	100	0.26	c	rs

Cross section : 5 — Morphological Unit : Plane bed

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	220	0.24	b	sbt
2	160	0.06	b	bpf
3	170	0.17	b	rs
4	160	0.04	b	rs
5	240	0.36	c	rs
6	300	0.18	c	rs
	200	0.11	b	rs

Cross section : 6 — Morphological Unit : Plane bed

No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	200	0.2	b	sbt
2	260	0.22	b	bpf
3	200	0.12	b	rs
4	220	0.15	b	rs
5	100	0.22	c	rs
6	140	0.08	c	rs
	110	0.03	b	rs

ELANDS

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

	Cross section :		5 & 6		Cross section :		3&4		Cross section :		1 & 2	
	Morphological Unit :		Pool		Morphological Unit :		Rapid		Morphological Unit :		Plane bed	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	420	0.01	c	bpf	120	0.84	c	bsw	180	0.04	b	sbt
2	270	0.05	b	bpf	160	0.87	b	sbt	200	0.09	b	usw
3	500	0.1	c	sbt	240	0.67	b	bsw	240	0.22	c	rs
4	340	0.13	c	sbt	260	0.6	c	bsw	280	0.29	b	rs
5	300	0.13	b	sbt	120	0.52	b	usw	580	0.15	b	sbt
6	500	0.12	c	sbt	200	0.49	b	usw	740	0.29	c	rs
7	660	0.13	g	sbt	260	0.7	c	bsw	320	0.28	b	sbt
8	260	0.02	s	bpf	240	0.18	c	usw	300	0.12	c	rs
9	640	0.03	c	bpf	200	0.92	b	bsw	480	0.14	c	rs
10	710	0.04	c	bpf	200	0.14	b	rs	500	0.38	b	sbt
11	470	0.11	b	sbt	150	0.88	b	sbt	560	0.32	b	rs
12	550	0.08	c	sbt	150	0.8	b	bsw	120	0.41	b	sbt
13	600	0.11	b	sbt	150	1.18	c	bsw	330	0.04	b	rs
14	440	0.05	b	bpf	260	0.17	c	rs	600	0.42	c	sbt
15	850	0.04	c	bpf	260	0.25	b	bsw	300	0.37	b	sbt
16	520	0.07	b	sbt	380	0.46	c	usw	480	0.15	c	sbt
17	560	0.04	b	sbt	300	0.34	c	usw	370	0.27	b	sbt
18	450	0.02	c	bpf	120	0.1	c	rs	280	0.03	c	bpf
19	230	0.04	b	bpf	380	0.52	c	usw	520	0.22	b	rs
20	340	0.03	s	bpf	260	0.29	b	bsw	400	0.15	b	rs
21	580	0.01	b	bpf	220	0.42	c	usw	460	0.02	g	bpf
22	420	0.02	b	bpf	200	0.8	b	bsw	180	0.27	b	rs
23	600	0.01	g	bpf	240	0.17	c	usw	540	0.21	c	sbt
24	610	0.03	b	bpf	200	0.56	c	usw	460	0.17	b	sbt
25	580	0.04	c	bpf	260	0.51	b	usw	400	0.18	c	rs
26	400	0.04	b	bpf	180	0.78	c	bsw	410	0.34	c	rs
27	700	0.12	g	sbt	360	0.36	b	usw	340	0.35	b	rs
28	700	0.09	b	sbt	400	0.4	c	rs	620	0.03	b	sbt
29	1080	0.11	b	bpf	440	0.2	b	rs	520	0.16	b	rs
30	1120	0.07	c	bpf	320	0.15	c	rs	380	0.31	c	rs

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

	Cross section :		1		Cross section :		2		Cross section :		3	
	Morphological Unit :		Plane bed		Morphological Unit :		Plane bed		Morphological Unit :		Rapid	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	450	0.12	c	sbt	260	0.29	c	usw	320	0.37	c	usw
2	220	0.17	b	sbt	220	0.08	g	rs	300	0.5	b	usw
3	380	0.13	b	sbt	120	0.15	b	rs	240	0.22	b	usw
4	350	0.25	b	rs	380	0.4	b	sbt	360	0.68	b	usw
5	500	0.24	c	rs	360	0.13	b	rs	200	0.15	b	rs
6	470	0.1	g	sbt	380	0.44	c	rs	280	0.08	c	rs
7	320	0.12	b	rs	240	0.23	b	sbt	430	0.48	b	usw
8	600	0.28	b	rs	440	0.09	c	rs	320	0.25	b	usw
9	380	0.17	b	rs					220	0.25	b	usw
10	420	0.03	b	bpf					180	0.2	c	usw

	Cross section :		4		Cross section :		5		Cross section :		6	
	Morphological Unit :		Rapid		Morphological Unit :		Pool		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	200	0.12	c	rs	200	0.01	s	bpf	530	0.08	c	sbt
2	220	0.3	c	rs	220	0.04	b	bpf	570	0.09	c	sbt
3	200	0.35	c	usw	300	0.01	b	bpf	530	0.07	b	sbt
4	120	0.69	b	sbt	220	0.01	b	bpf	520	0.1	c	sbt
5	120	0.3	c	bsw	520	0.04	c	bpf	320	0.13	b	sbt
6	240	0.24	c	usw	540	0.01	c	bpf	450	0.15	c	sbt
7	300	0.3	c	usw	680	0.02	c	bpf	420	0.11	b	sbt
8	220	0.43	c	usw	400	0.06	b	sbt	580	0.06	c	sbt
9	240	1.04	c	sbt	660	0.07	c	sbt	180	0.18	b	sbt
10	200	0.82	c	bsw	860	0.06	b	sbt	280	0.18	c	sbt
11	120	0.52	b	usw	1120	0.09	c	sbt	140	0.13	b	sbt
12	360	0.54	b	usw	1120	0.09	c	sbt	260	0.03	g	bpf
13	260	0.3	b	rs	1120	0.09	c	sbt				
14	120	0.43	c	usw	1120	0.09	c	sbt				
15	80	0.54	c	usw								

BERG II

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

	Cross section : 1				Cross section : 2			
	Morphological Unit : Rapid				Morphological Unit : Pool			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	440	0.54	b	bsw	260	0.09	b	sbl
2	310	0.21	c	usw	410	0.03	g	bpf
3	220	0.61	c	bsw	630	0.14	c	sbl
4	120	0.04	c	rs	280	0.06	g	bpf
5	140	0.26	b	usw	190	0.04	c	bpf
6	230	0.43	c	bsw	280	0.01	g	bpf
7	80	0.47	b	sbl	530	0.05	b	bpf
8	100	0.51	c	bsw	340	0.16	c	sbl
9	110	0.27	c	usw	420	0.14	c	sbl
10	80	0.68	b	sbl	500	0.08	b	bpf
11	210	0.8	c	bsw	680	0.07	c	bpf
12	80	0.76	b	sbl	360	0.12	c	sbl
13	230	0.73	c	bsw	350	0.26	c	rs
14	120	0.02	g	bpf	410	0.07	c	bpf
15	180	0.5	c	usw	210	0.07	c	sbl

	Cross section : 4				Cross section : 5			
	Morphological Unit : Pool				Morphological Unit : Rapid			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	310	0.02	g	bpf	230	0.88	c	bsw
2	280	0.09	b	sbl	330	0.38	c	usw
3	580	0.08	c	sbl	100	0.72	b	sbl
4	350	0.13	b	sbl	180	0.28	c	usw
5	460	0.02	g	bpf	220	0.47	c	bsw
6	200	0.01	c	bpf	80	0.48	c	usw
7	330	0.01	g	bpf	170	0.45	b	usw
8	420	0.02	c	bpf	210	0.62	c	usw
9	590	0.08	c	sbl	200	0.22	c	rs
10	220	0.13	b	sbl	130	0.05	g	rs
11	370	0.04	g	bpf	200	0.61	c	usw
12	240	0.08	c	sbl	80	0.24	b	rs
13	320	0.13	c	sbl	160	0.32	b	usw
14	350	0.03	c	bpf	250	0.51	c	bsw
15	110	0.01	g	rf	200	0.35	c	usw

	Cross section : 3			
	Morphological Unit : Plane bed			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	230	0.44	c	rs
2	240	0.57	c	usw
3	150	0.03	c	bpf
4	180	0.3	b	rs
5	200	0.26	c	rs
6	250	0.74	b	bsw
7	280	0.23	g	rs
8	280	0.13	b	rs
9	180	0.39	c	rs
10	270	0.34	c	rs
11	290	0.19	c	rs
12	200	0.2	b	rs
13	240	0.45	c	rs
14	200	0.42	c	usw
15	210	0.36	c	rs
16	250	0.55	b	usw
17	310	0.29	c	rs
18	200	0.37	g	rs
19	220	0.10	b	rs
20	250	0.18	c	sbl
21	240	0.01	g	bpf
22	140	0.03	c	bpf
23	280	0.21	c	rs
24	230	0.31	c	usw
25	230	0.2	c	rs
26	80	0.04	c	rs
27	210	0.27	c	usw
28	210	0.45	c	usw
29	180	0.18	c	rs
30	190	0.27	c	rs

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

	Cross section : 1				Cross section : 2			
	Morphological Unit : Rapid				Morphological Unit : Pool			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	50	0.38	g	usw	280	0.01	g	bpf
2	60	0.25	c	usw	140	0.07	b	sbl
3	60	0.1	c	s/f	330	0.04	c	sbl
4	90	0.3	b	sbl	430	0.06	b	sbl
5	100	0.47	b	sbl	340	0.13	b	sbl
6	130	0.36	c	bsw	400	0.07	c	sbl
7	330	0.02	c	rs	400	0.04	c	sbl
8	420	0.64	b	bsw	340	0.11	c	sbl
9					260	0.09	c	sbl
10					400	0.09	c	sbl
11					440	0.02	br	bpf

Cross section : 3			
Morphological Unit : Plane bed			
Depth (mm)	Velocity (m/s)	Substrate	Flow Type
160	0.14	g	rs
180	0.24	c	rs
170	0.17	c	usw
100	0.27	c	usw
140	0.09	g	rs
260	0.08	c	rs
220	0.19	c	rs
120	0.5	c	usw
130	0.26	c	rs

	Cross section : 4				Cross section : 5			
	Morphological Unit : Pool				Morphological Unit : Rapid			
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	60	0	c	rf	40	0.04	g	rs
2	170	0.01	c	bpf	150	0.05	c	bpf
3	400	0.02	g	bpf	140	0.03	c	bpf
4	500	0.08	c	sbl	160	0.4	c	usw
5	400	0.16	c	sbl	140	0.42	c	bsw
6	410	0.09	g	sbl	180	0.48	c	bsw
7	270	0.01	b	bpf	170	0.67	c	bsw
8					60	1.33	c	bsw
9					220	0.33	c	usw
10					220	0.01	g	bpf
11					90	0.03	g	rs

BERG I

A : RANDOM HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA WITHIN MORPHOLOGICAL UNITS

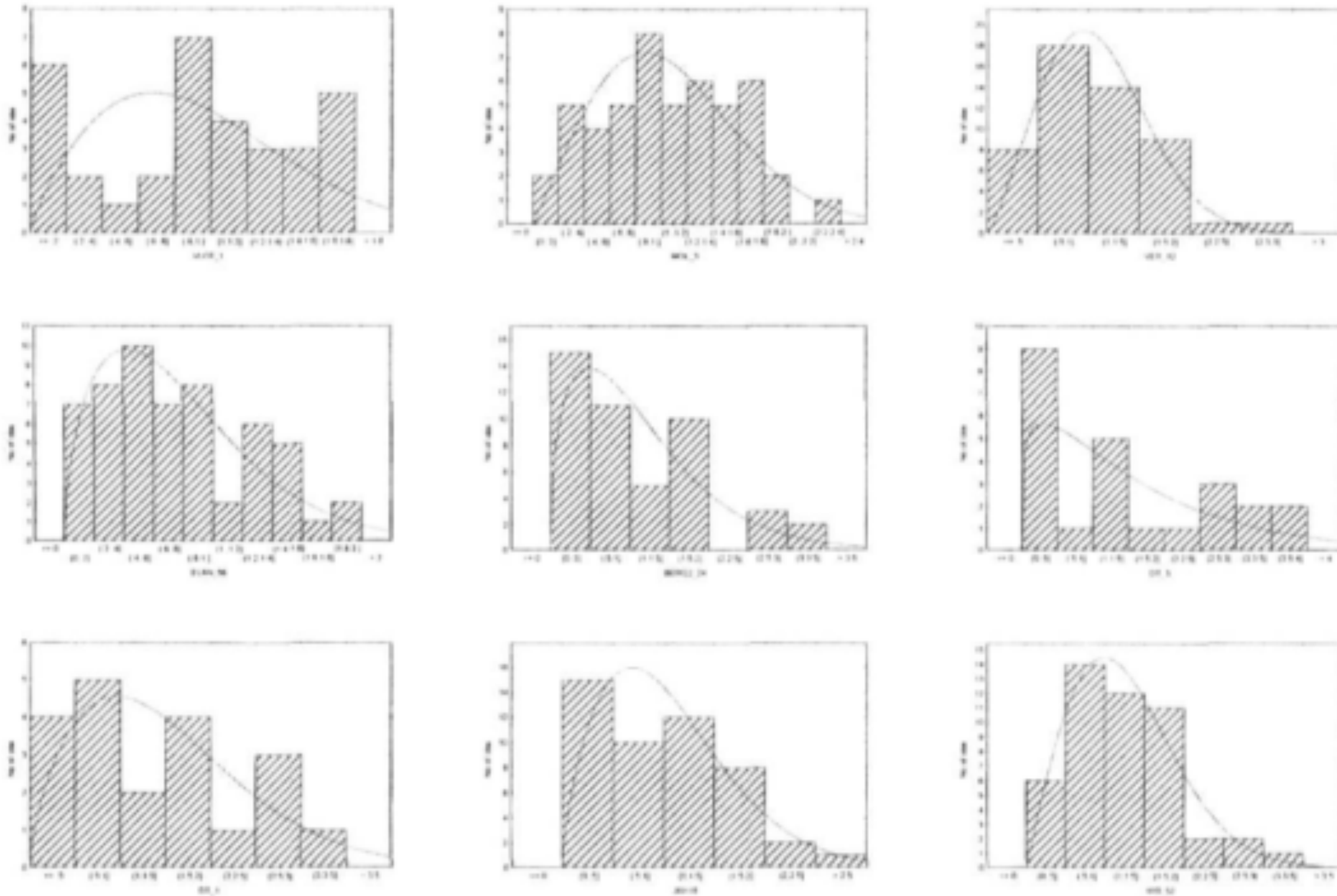
	Cross section :		1 & 2		Cross section :		3 & 4		Cross section :		5	
	Morphological Unit :		Plane bed		Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	190	0.16	g	rs	140	0.29	c	usw	180	0.02	c	bpf
2	200	0.19	c	rs	200	0.27	c	usw	270	0.01	c	bpf
3	160	0.18	b	rs	120	0.3	c	usw	600	0.03	c	bpf
4	210	0.11	g	rs	180	1.1	b	bsw	430	0.03	c	bpf
5	180	0.19	g	sbt	260	0.17	c	rs	240	0.01	b	bpf
6	230	0.18	c	rs	190	0.17	c	rs	290	0.02	g	bpf
7	200	0.12	b	sbt	100	0.98	c	bsw	210	0.01	g	bpf
8	220	0	c	nf	110	0.57	c	usw	320	0.01	b	bpf
9	230	0.06	c	sbt	120	0.63	c	sbt	480	0.02	c	bpf
10	260	0.31	c	rs	120	0.57	b	usw	600	0.04	c	bpf
11	230	0.23	b	rs	160	1.01	c	bsw	660	0.01	b	bpf
12	270	0.15	c	rs	130	0.41	c	usw	620	0.01	c	bpf
13	160	0.23	b	rs	70	0.36	c	usw	460	0.01	c	bpf
14	230	0.08	c	sbt	140	0.64	c	bsw	550	0.01	b	bpf
15	200	0.15	c	sbt	280	0.38	b	usw	400	0.02	b	bpf
16	220	0.13	c	rs	160	0.01	c	bpf	390	0.04	b	bpf
17	240	0.17	b	rs	340	0.16	c	rs	550	0.02	b	bpf
18	330	0.18	c	rs	270	0.47	c	usw	580	0.03	c	bpf
19	360	0.02	c	bpf	210	0.52	b	usw	600	0.05	c	bpf
20	370	0.016	b	rs	230	0.45	c	bsw	390	0.05	b	sbt
21	460	0.01	c	bpf	180	0.83	b	sbt	530	0.07	c	sbt
22	320	0.08	c	sbt	140	0.64	c	usw	520	0.03	c	bpf
23	210	0.13	c	rs	80	0.81	b	bsw	270	0.03	b	bpf
24	310	0.13	c	rs	150	0.88	b	bsw	440	0.01	c	bpf
25	230	0.08	g	sbt	110	1.2	b	usw	490	0.01	c	bpf
26	340	0.13	c	sbt	120	0.47	c	usw	260	0.01	g	bpf
27	300	0.14	b	sbt	100	0.58	b	usw	150	0.01	c	bpf
28	480	0.22	b	rs	270	0.37	c	rs	100	0.05	b	sbt
29	200	0.18	c	rs	250	0.17	b	rs	340	0.02	c	bpf
30	150	0.16	c	rs	60	0.84	b	sbt	260	0.02	c	bpf

B : HYDRAULIC-, FLOW TYPE- AND SUBSTRATE DATA IN SPECIFIC CROSS SECTIONS

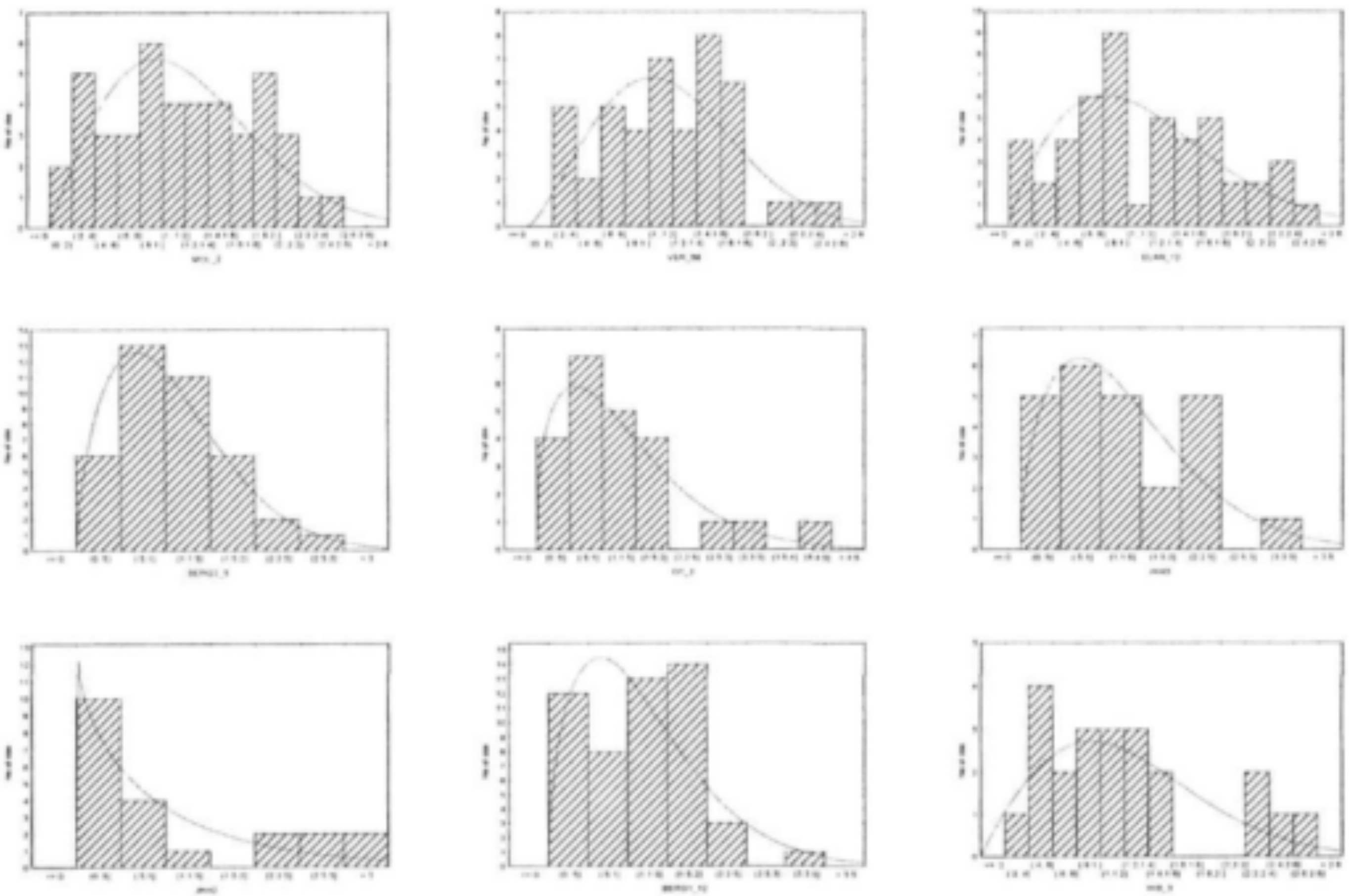
	Cross section :		1		Cross section :		2		Cross section :		3	
	Morphological Unit :		Plane bed		Morphological Unit :		Plane bed		Morphological Unit :		Rapid	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	100	0	b	nf	80	0.04	c	rs	130	0.19	c	rs
2	110	0.03	c	bpf	280	0.01	c	bpf	290	0.1	c	rs
3	310	0.01	g	bpf	270	0.01	b	bpf	220	0.21	c	rs
4	400	0.12	c	sbt	320	0.05	b	sbt	120	0.13	c	rs
5	320	0.12	b	sbt	190	0.11	b	rs	120	0.44	c	bsw
6	460	0.04	c	bpf	60	0.01	b	bpf	110	0.79	b	bsw
7	400	0.01	g	bpf	100	0.09	c	rs	80	0.63	b	sbt
8	270	0.16	b	rs	230	0.11	b	rs	140	0.50	c	usw
9	220	0.19	c	rs	280	0.14	c	rs	120	0.46	c	usw
10	190	0.03	b	bpf	200	0.17	c	rs	90	0.25	c	bsw
11	110	0.06	c	sbt	150	0.14	b	rs	170	0.24	b	rs
12					200	0.08	c	rs	70	0.29	b	usw

	Cross section :		4		Cross section :		5	
	Morphological Unit :		Rapid		Morphological Unit :		Pool	
No.	Depth (mm)	Velocity (m/s)	Substrate	Flow Type	Depth (mm)	Velocity (m/s)	Substrate	Flow Type
1	90	0.03	b	bpf	350	0	g	nf
2	50	0.13	c	usw	350	0.02	b	bpf
3	120	0.25	c	bsw	450	0.01	b	bpf
4	100	0.72	b	sbt	420	0.02	c	bpf
5	180	0.39	c	bsw	520	0.01	b	bpf
6	100	0.51	b	bsw	680	0.04	c	bpf
7	200	0.2	c	rs	360	0.04	b	bpf
8	120	0.54	b	sbt	500	0.01	c	bpf
9	110	0.43	c	bsw	280	0.01	b	bpf
10	120	0.17	c	rs	360	0.01	b	bpf
11	140	0.09	c	rs	170	0.02	g	bpf
12	80	0.45	c	usw				

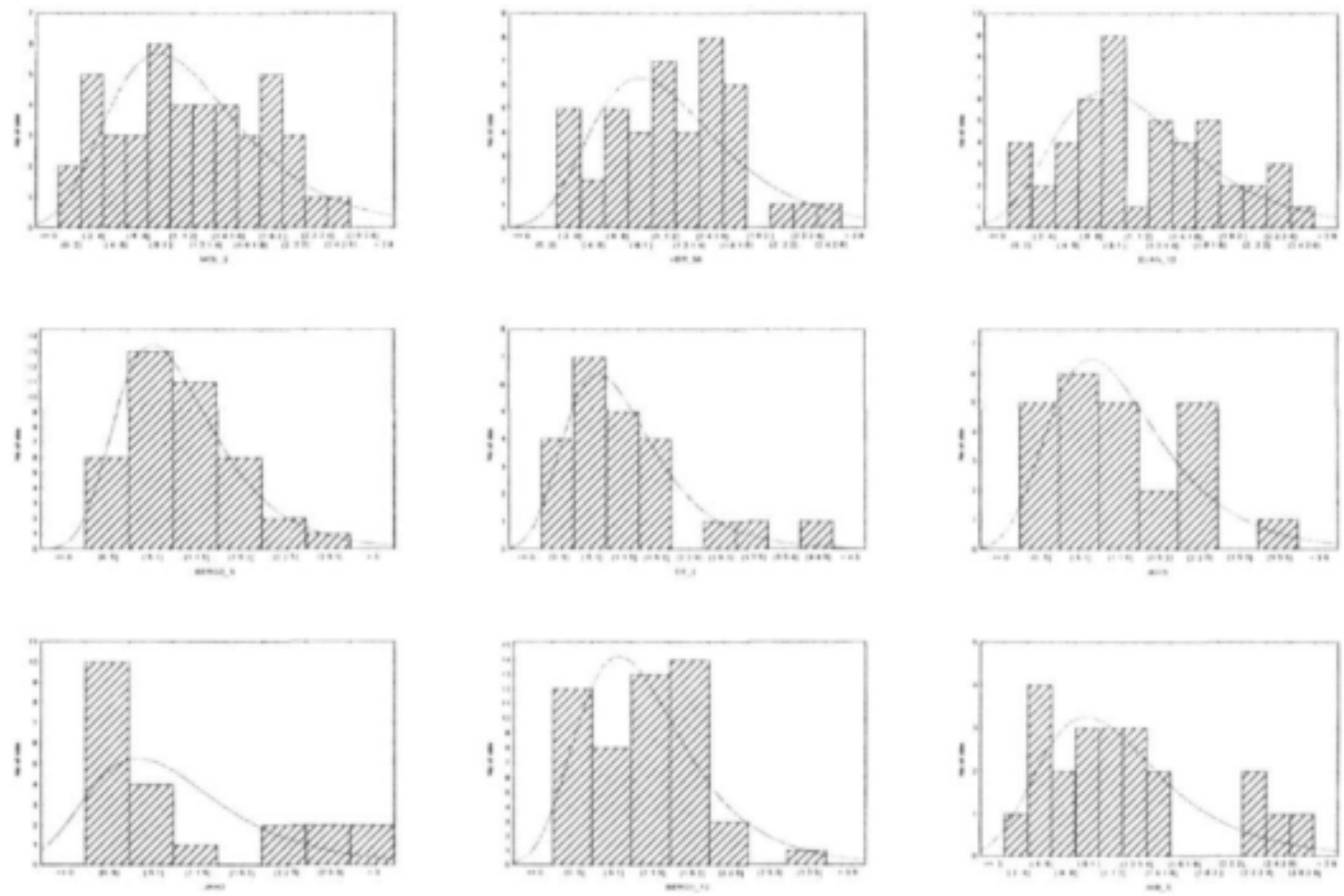
APPENDIX J: Histograms of relative point velocity



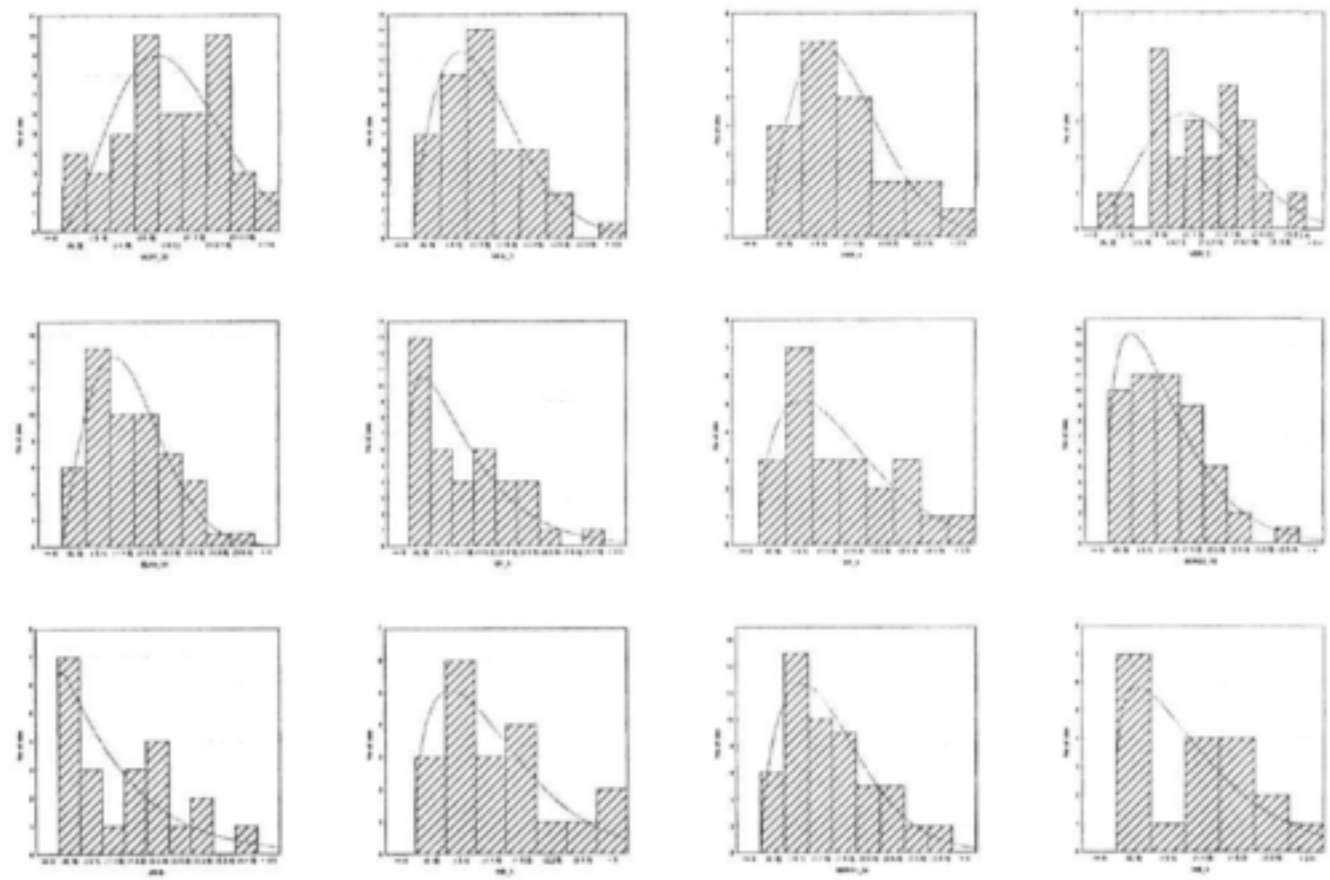
POOLS : Weibull distribution fitted



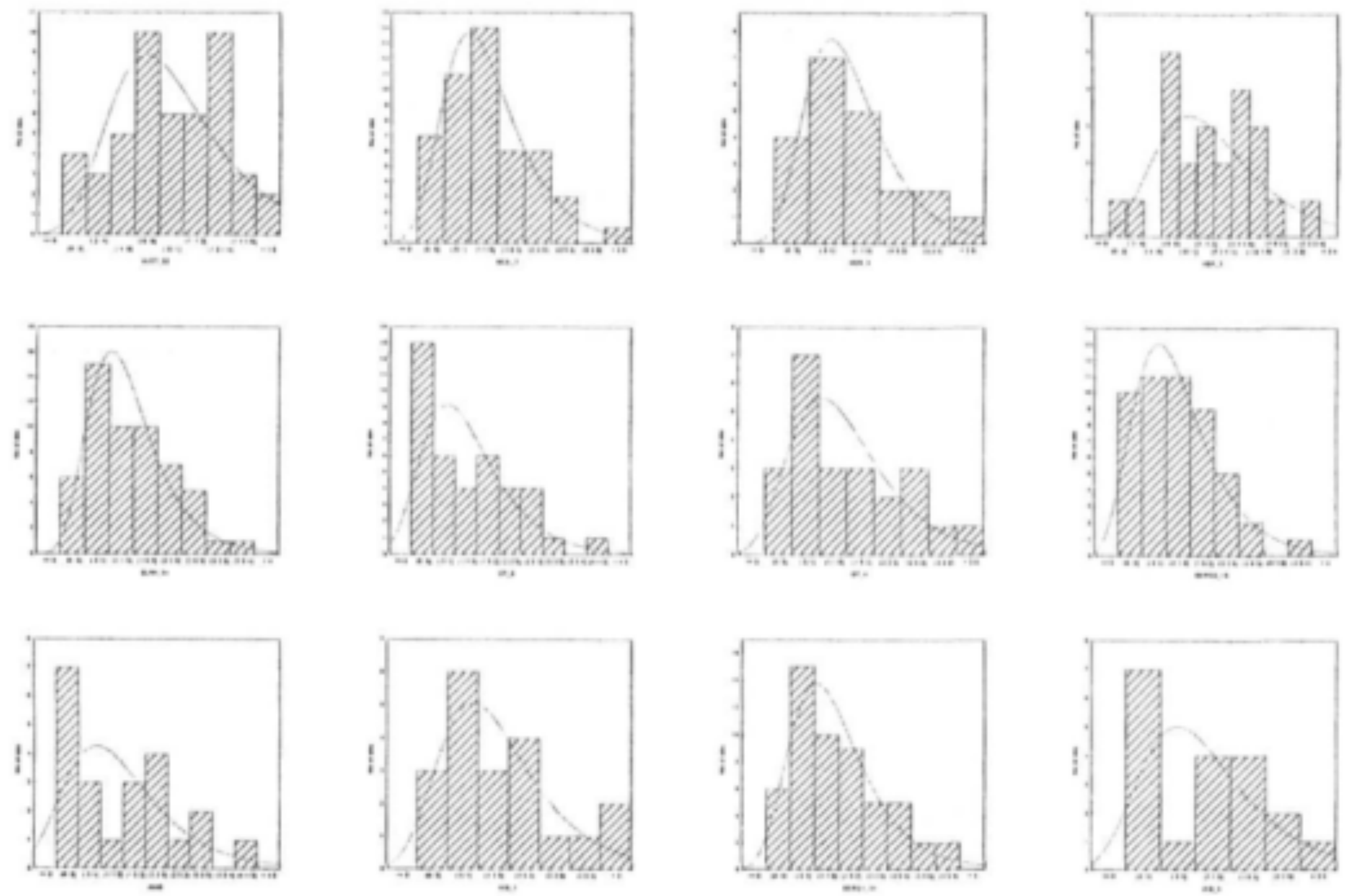
PLANE BEDS: Weibull distribution fitted



PLANE BEDS: Extreme Type I distribution fitted



RAPIDS and RIFFLES : Weibull distribution fitted



RAPIDS and RIFFLES: Extreme Type I distribution fitted

Other related WRC reports available:

Discharge measurement in terms of pressure differences at bridge piers
C Meyer, A Rooseboom, MJ Retief, GC Cloete

This study entailed the successful investigation and evaluation of a new methodology for measuring high discharges passing through bridges. Pressure differences generated around bridge piers have been measured and related to discharges. These pressure differences are mainly functions of downstream flow conditions. The pressure differences have been converted into velocities by applying Newton's second law expressed in terms of the laws of conservation of energy, momentum, and of power.

Report Number: 980/3/00 **ISBN: 1 86845 665 X**

The rating of sluicing flumes in combination with sharp-crested and crump weirs under modular and non-modular flow conditions
H Bruce , J Rossouw, A Rooseboom

As part of a previous WRC project, three types of sluicing flumes were developed for use in compound weirs in combination with sharp-crested and Crump weirs, (Rossouw et al., 1998). These sluicing flumes have several advantages which make them ideal structures for flow measurement in South African rivers. These are a high modular limit, stable modular flow characteristics, an ability to measure a wide range of flows accurately, as well as good sediment handling characteristics. These three flumes have been calibrated under modular or free flow conditions in combination with sharp-crested and Crump weirs.

There is a high degree of variability of flow in South African rivers. Flood discharges are part of this variability, and can form an important part of the mean annual runoff. Measuring weirs cannot always be built so that they do not become submerged during floods, but it is nevertheless important that flood discharges be recorded. It is therefore important that these compound weirs be calibrated for flow measurement under non-modular or submerged conditions.

Report Number: 980/2/00 **ISBN: 1 86845 663 3**

TO ORDER: Contact **Rina** or **Judas** - Telephone No. 012 330 0340
Fax Number; 012 331 2565
E-mail: publications@wrc.org.za

1868457354

Water Research Commission
Private Bag X03, Gezina, 0031, South Africa
Tel: +27 12 330 0340, Fax: +27 12 331 2565
Web: http://www.wrc.org.za