THE DEVELOPMENT OF A HYDRAULIC MODEL FOR DETERMINING BED DISTURBANCE DUE TO FLOODS IN COBBLE AND BOULDER BED RIVERS

Report to the
Water Research Commission

by

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This report forms part of a series of two reports. The other report in this series is" Flood Disturbance Responses of Invertebrate Assemblages in Two Cobble-Boulder Bed Rivers of the Western Cape" (WRC Report No 1411/2/08).

Project Leader: Professor A Rooseboom

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LIST OF SYMBOLS AND ABBREVIATIONS

a, b, c : Constants
A : Cross sectional flow area
C_d : Drag coefficient
C_x : Large scale roughness coefficient
d : Particle diameter
d_x : Particle size for which x % is smaller
D : Flow depth
DC : DRIFT flood class
EFR : Ecological Flow Requirements
Fr : Froude number
*F** : Particle densimetric Froude Number
g : Gravitational acceleration
I : Intensity of movement
k : Absolute bed roughness
M : Movability number
PM : Probability of movement
Q : Discharge
r : Rate of increase of percentage of movement
Re : Reynolds' number
Re_* : Particle Reynolds' number
s : Energy slope
S_f : Energy gradient
S_0 : Bed slope
U : Mean velocity
v : Kinematic viscosity
V_{ss} : settling velocity
y : distance above bed
z : bed elevation above datum
α : descriptive reach parameter
κ : Von Karman "constant"
θ : Shield's parameter
θ_{crit} : Critical Shield's parameter
μ : Dynamic viscosity
ρ : Density of water
ρ_s : Particle density
τ_0 : Bed shear stress
τ_{crit} : Critical bed shear stress

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EXECUTIVE SUMMARY

Introduction

This is an Extended Executive Summary for two Reports that present the findings of the Water Research Commission (WRC) Research Project K5/1411 entitled: *Determination of Substrate Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations.* The two Reports, which can be obtained from the Water Research Commission of South Africa, are titled:

- *The Development of a Hydraulic Model for Determining Bed Disturbance Due to Floods in Cobble and Boulder Bed Rivers (WRC Report No 1411/1/07)*
- *Flood Disturbance Responses of Invertebrate Assemblages in Two Cobble and Boulder Bed Rivers of the Western Cape(WRC Report No 1411/2/07)*

The first Report, referred to as the Hydraulics Report, outlines the development of a mathematical hydraulic model used to predict bed disturbance under particular flood events. A simple empirical model relates the DRIFT flood class to the intensity of movement (i.e. the total percentage of cobbles that move), and a more detailed model that looks at the probability of movement of individual stones in cobble and boulder bed rivers based on a critical Movability Number that represents the ratio of applied power to required power. This Report also presents preliminary guidelines for the determination of substrate maintenance flow requirements for cobble and boulder bed rivers based on the findings of the aforementioned two Reports.

The second Report, referred to as the Ecological Disturbance Report, considers the relationship between bed disturbance due to flood events and the impact and response of invertebrate assemblages in the two observed cobble and boulder bed rivers in the Western Cape. This Report also analyses the distribution of invertebrates during winter base-flow conditions and relates this to stone size and various hydraulic variables.

Aims and Objectives

The overall objective of this research project is to lay the foundation for the development of guidelines for the determination of substrate maintenance flow requirements to ensure the sustainability of cobble and boulder bed river ecosystems. The specific aims required to attain this objective are addressed in terms of the following deliverables:

1. Develop a theoretically based hydraulic model that will address the relationship between discharge and substrate disturbance in cobble and boulder bed rivers.

2. Define and quantify ecologically significant substrate disturbance levels in cobble and boulder bed rivers.
3. Develop guidelines for the specification of substrate maintenance flow components in cobble and boulder bed rivers.

The above aims have been met through the collection and analysis of data from two flood seasons on two mountain streams in the Western Cape of South Africa. The results of these deliverables are presented and discussed in the two reports referred to earlier and are summarised in this extended executive summary.

Literature Review

A literature review was undertaken to synthesise current knowledge on existing hydraulic models for incipient motion in cobble and boulder bed rivers, and on stream ecosystem disturbance by floods. The latter topic included consideration of existing approaches to both the measurement of the disturbance event and the quantification of the disturbance response by stream invertebrates and periphyton as a major food source in open-canopied rivers.

Data Collection

The research was conducted in two relatively undisturbed mountain streams in the Western Cape, the Molenaars River and the Berg River. Close to 800 stones ranging in size from 25 mm to 1100 mm per median diameter were marked, 345 in the Molenaars and 435 in the Berg, just prior to the start of the flood season. The dimensions of each stone were recorded in terms of the three major axes and the base-flow hydraulic characteristics of depth and velocity were also recorded. In addition, samples were taken for the analysis of invertebrates and periphyton.

The movement or non-movement of the marked stones was recorded after each of thirteen flood events at both study sites. The floods ranged from small freshettes that resulted in negligible disturbance to bankfull floods. The largest observed flood resulted in the movement of 44% of the marked stones at one of the study sites. After each flood event, the marked stones were located and returned to their original position in preparation for the next event. In addition to recording the movement or non-movement of stones, pre- and post-flood sampling was done of the invertebrate and periphyton communities for a number of flood events to determine the level of disturbance due to the flood events.

Hydraulic model to predict movement of individual stones

A theoretical mathematical model was first developed based on the theory of applied power. This model defines incipient motion as the point at which a stone is more likely to move than to not move (i.e. the critical value is when the probability of movement is greater than 50%). The theory of unit stream power was used to develop a Movability Number that represents the ratio of applied power to required power in cobble and boulder beds with non-uniform bed material.

The critical value was determined using the observed data as:

$$\frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} = 0.12$$

with *D* : flow depth, measured down to the top of the stone.

d : individual stone diameter measured on the second longest axis

s : energy slope

V_{ss} : Turbulent settling velocity ($V_{ss} = \sqrt{\frac{4(\rho_s - \rho)gd}{3\rho C_d}}$)

k : absolute bed roughness (*k* = minimum of d_{84} or D)

d_{84} : particle diameter for which 84% of particles are smaller

C_d : drag coefficient ($C_d = 0.4$)

ρ : density of water

ρ_s : density of particle

g : acceleration due to gravity ($g = 9.81$ m/s^2)

For uniform beds the absolute roughness can be represented by the average stone size (i.e. *k* = *d*). In this case the equation is equal to that found to represent the threshold of movement on uniform beds by Rooseboom (1998) as depicted in the Liu Diagram.

In addition to the initially marked and sampled stones, a number of additional stones were also sampled for invertebrates and periphyton after a series of flood events. The above model was used to determine whether these additional stones would have been likely to have moved under the previous flood events. These stones were used to extend the analysis of the impact of flood disturbance on invertebrate assemblages and as a control for the impact of the initial sampling method.

It is important to note that this relationship was developed using data obtained from only thirteen flood events and from only two streams. The average bed slope of the Molenaars study reach was 0.018 m/m and for the Berg studies reach it was 0.015 m/m. The observed particles were all in the cobble to boulder range with a maximum stone size of just over 1m in diameter. The d_{84} for the Molenaars study reach was 538 mm while the d_{84} for the Berg study reach was 372 mm. The d_{50} for the Molenaars study reach was 248 mm while the d_{50} for the Berg study reach was 205 mm.

It is unclear at this stage if this represents a universal finding for all rivers of non-uniform particle size distribution. To be able to answer this will require the model to be tested on other rivers. The results from the two rivers tested, however, where consistent despite being of different size and having different stone size distribution. Based on this observation it could be hypothesized that the above results will be universal at least in the case of cobble and boulder bed rivers.

Average Bed Disturbance in Relation to DRIFT Flood Class

A second empirical model was also developed that related the intensity of movement or stream competence to the DRIFT flood classification. This relationship was described by the equation:

$$I = \frac{e^{34.3.\alpha.DC}}{96.9.\alpha} \quad \text{with} \quad \alpha = S_0 \frac{d_{84}}{d_{50}}$$

where I = the intensity of movement as a percentage
DC = the DRIFT flood classification
S_0 = the average bed slope
d_{84} = the median stone diameter for which 84% are smaller
d_{50} = the median stone diameter for which 50% are smaller

It is important to note that this reach factor (α) is only provisional at this stage. The above relationship is based on a few samples in only two rivers in the Western Cape. The above equation is therefore a proposal for a possible form of universal relationship between the intensity of movement (I), the DRIFT flood class (DC) and the specific reach characteristics (α). Further research and testing of this relationship on other rivers is important before the above relationship can be considered for use in environmental flow assessments and rehabilitation studies.

This relationship will enable scientists to get a first order estimate of the level of disturbance likely to be associated with a particular flood class for cobble and boulder bed rivers. This can then be used to set the required flood magnitude for the desired level of ecological disturbance. It will also enable the practitioner to make a more informed judgement on the impact of having more or less flood of a certain class in the managed flow regime as part of the DRIFT flood classification methodology.

Relationship between Invertebrate Fauna and Hydraulic Variable

A baseline survey of the invertebrate fauna of both rivers showed that invertebrate assemblages in the Molenaars River appeared to have stronger relationships than was the case in the Berg River, between their density distribution and hydraulic parameters such as point measurements of velocity, depth, or defined in terms of hydraulic biotopes. The most significant relationships identified through analysis of the baseline survey data, however was a negative linear correlation between invertebrate density and stone particle size for both the Berg and Molenaars Rivers, which indicates that some 25 - 31% of overall invertebrate density can be explained by particle size. The strength of this relationship varied between taxa with only a few taxa exhibiting a positive association with particle size. More taxa were significantly correlated with stone particle size than any other variables.

Post Disturbance Recovery: The Molenaars River Study Site

Ecological data were only collected at the Molenaars site in 2003. This happened to be a very dry year and as a result the floods analysed with pre- and post-flood sampling were very small and resulted in less than 3% of bed disturbance. The study data were then best used to examine recovery processes after an initial disturbance - the initial denudation of stones during the pre-season sampling - emulating artificial disturbance studies prevalent in the scientific literature.

Recovery rates of the invertebrate taxa following initial disturbance were highly variable, and recovery was slower than that measured in other studies. Species-specific responses were identified and explained, in terms of mobility, population structure and initial population densities, as well as recovery rates of periphyton and food resource quality on disturbed substrata. Some findings indicating high levels of micro-habitat specificity and potential competitive interactions were also discussed.

The minor floods that occurred during the sampling period affected the recovery of invertebrates on denuded substrata to different degrees. In some of the taxa which had shown little initial recovery, the increased velocities associated with the floods were considered to have increased effective mobility and facilitated recolonisation.

Where recovery after initial sampling was rapid, the taxa exhibited various responses to the small flood events, ranging from apparent flood-induced emergence, or susceptibility of only large instars to floods, through various levels of susceptibility of the population to increased flows, including no measurable response to increased flows. In other words, there are large differences in the extent to which species perceive small floods as disturbance.

These species-specific responses to small flood flows are summarised in **Table 1**. It should be noted that these data must be considered preliminary, since the patchiness of invertebrate distributions, especially when abundances were low, as well as the wide variance associated with estimates of population density precluded statistically significant results in most instances. Nevertheless, they do represent the first species-level data for flood-related responses on invertebrates in Western Cape rivers.

Table 1: Summarised species-specific responses to small early winter floods in the Molenaars River, 2003

SPECIES / TAXON	SUSCEPTIBILITY TO FLOODS	
	Description	**Change in density over flood period**
Species showing high resilience (good / full recovery after initial sampling, before floods)		
Afroptilum spp.	differential loss small instars	↓
Demoreptus capensis	recruitment of new instars	≈
Pseudocloeon sp.		↓↓
Euthraulus elegans		≈
Lithogloea harrisoni	recruitment of new instars	↑↑↑
Afronurus harrisoni	differential loss large instars or flood-mediated emergence	↓↓
Afronurus sp.		↓↓
Notonemouridae	recruitment of new instars	↑↑↑
Simulium spp.	recruitment of new instars	↑↑↑
Orthocladinae		≈
Tanypodinae		↓↓
Helodidae		≈
Hydrachnellae		↓
Species showing medium resilience (moderate recovery after initial sampling, before floods)		
Baetis spp.	may be associated with food quality	↓
Demoulinia spp.		↓
Lestagella penicillata		≈
Aprionyx spp.	Autumn emergence - small numbers depleted by floods	↓↓↓
Tanytarcini		≈
Chironomini		≈
Species showing low resilience (poor or no recovery after initial sampling, before floods)		
Cheumatopsyche afra		food-facilitated partial recovery
Chimarra sp.		flood-facilitated partial recovery
Agapetus agilis	recruitment of new instars	pattern not clear
Elporia spp.	recruitment of new instars	≈
Elmidae larvae		flood-facilitated partial recovery
Elmidae adults		↓

Note: The resilience of different taxa is indicated categorically as 'high', 'medium' or 'low', based on the extent of recovery observed in the month after initial baseline sampling, but prior to floods. Susceptibility to flow is also provided within categories of percentages, because of the low level of significance in the results. These categories are as follows: ≈- no change (± 24% increase or decrease); ↓ (25 - 69% decrease); ↓↓ (70 - 84% decrease); ↓↓↓ (85 - 100+% decrease). Arrows facing upwards indicate increases in density.

Invertebrate Responses to Large, Within-year Flood Events

In the Berg River in 2004 there were two large intra-annual floods during the study period that moved between 25 and 43% of the marked bed particles, and three minor spates (DRIFT Class I and II) that moved less than 3%. The larger floods represented a low and a high DRIFT Class IV flood, and moved all size categories of river bed materials (small cobble through to boulders), but to different degrees. These larger floods are more akin to descriptions of 'disturbance' used in the scientific literature, although the cumulative effect of small floods on population dynamics should not be ignored.

The floods in the Berg River were associated with some 58% decrease in total invertebrate density, cumulative for the two-month period. Nearly all individual invertebrate taxa declined significantly, whilst three mayfly taxa increased in densities on stones over the study period. The large floods on the Berg River appeared to exceed a disturbance threshold for other taxa that were not affected by the smaller floods on the Molenaars River, for example, species of Simuliidae.

The Berg River study allowed for the effects of stone movement or non-movement during floods to be described, in relation to the magnitude of the disturbance-response by invertebrates. The percentage decrease in total invertebrate density on stones that were unmoved over the whole study period, relative to those that moved in both large floods was 40% and 62% respectively, a difference of some 20%. This result indicates that, despite obvious flood-induced mortality, many taxa were still present in reasonable densities on moved stones - an unanticipated finding. These results also indicate a 'relative refugium' afforded to invertebrates on stable stones. Whilst this was only some 20% for total invertebrates, it was shown to be more or less important for different taxa. It is noteworthy, however, that a number of taxa virtually only survived floods because of the relative refugium of unmoved stones - viz. Leptophlebiidae, most Trichoptera, and the mayfly *Afroptilum spp*. Similarly, *Lithogloea harrisoni*, which appears on the river bed at the start of winter, only increased in population density on unmoved stones.

The responses to floods on both unmoved stones vs. those moved in both large floods are summarised in **Table 2**, for invertebrate taxa, which were represented in sufficient densities in order to show patterns. The susceptibility to flow is a measure of the extent to which the series of floods reduced population densities.

Table 2: Summarised species-specific responses to winter floods in the Berg River, 2004, showing the relative refugium from flood mortality afforded by unmoved stones.

SPECIES / TAXON	UNMOVED STONES		STONES MOVED IN BOTH LARGE FLOODS	
	Repeat-sampled	Additional	Repeat-sampled	Additional
No relative refugium offered on unmoved stones				
Demoreptus capensis	↓↓↓	↓↓	↑↑↑	↑↑↑
Notonemouridae	↓	↓	≈	↑
Simulium spp.	↓	↓↓	≈	≈
Demoulinia spp.	↓↓↓	↓↓↓	↓↓↓	↓↓↓
Cheumatopsyche afra	↓↓↓	↓↓↓	Not present in Baseline	
Tanypodinae	↓↓↓	↓↓↓	↓↓↓	↓↓↓
Orthocladinae	↓	↓	↓	↓
Elmidae adults	↓↓	↓↓↓	↓↓↓	↓↓
Elmidae larvae	↓↓	↓↓	↓↓↓	↓↓
Low relative refugium offered on unmoved stones				
Cheumatopsyche maculata	↓↓↓	↓↓	↓↓↓	↓↓↓
Athripsodes bergensis	↓↓	↓↓↓	↓↓↓	↓↓↓
Afronurus sp.	↓↓↓	↓↓	↓↓↓	↓↓↓
Aprionyx spp.	↓↓	↓↓↓	↓↓↓	↓↓↓
Chironomini	≈	≈	≈	↓
Baetis spp.	↓	≈	↓	↓
Hydrachnellae	↓	↓	↓↓	↓
Euthraulus elegans	↓↓	↓↓	↓↓↓	↓↓↓
Chimarra sp.	↓↓↓	↓	↓↓↓	↓↓↓
Afronurus harrisoni	↓	↓↓↓	↓↓	↓↓↓
Tanytarcini	↓↓	↓	↓↓↓	↓↓
Moderate to high relative refugium offered on unmoved stones				
Lestagella penicillata	↓	↓	↓↓↓	↓↓↓
Helodidae	↓	↓	↓↓↓	↓↓↓
Afroptilum spp.	↑	↑	↓↓↓	↓↓↓
Lithogloea harrisoni	↑↑↑	↑↑↑	↓	≈
Note: Susceptibility to flow is based on percentage reduction in population density, and provided within categories of percentages. These categories are as follows: ≈- no change (± 24% increase or decrease), ↓ (25 - 69% decrease); ↓↓ (70 - 84% decrease); ↓↓↓ (85 - 100+% decrease). Arrows facing upwards indicate increases in density.				

Summary of Flood Disturbance Response of Invertebrate Assemblages
The key findings of the analysis of flood disturbance responses of invertebrate assemblages in the two rivers studied are summarised below:

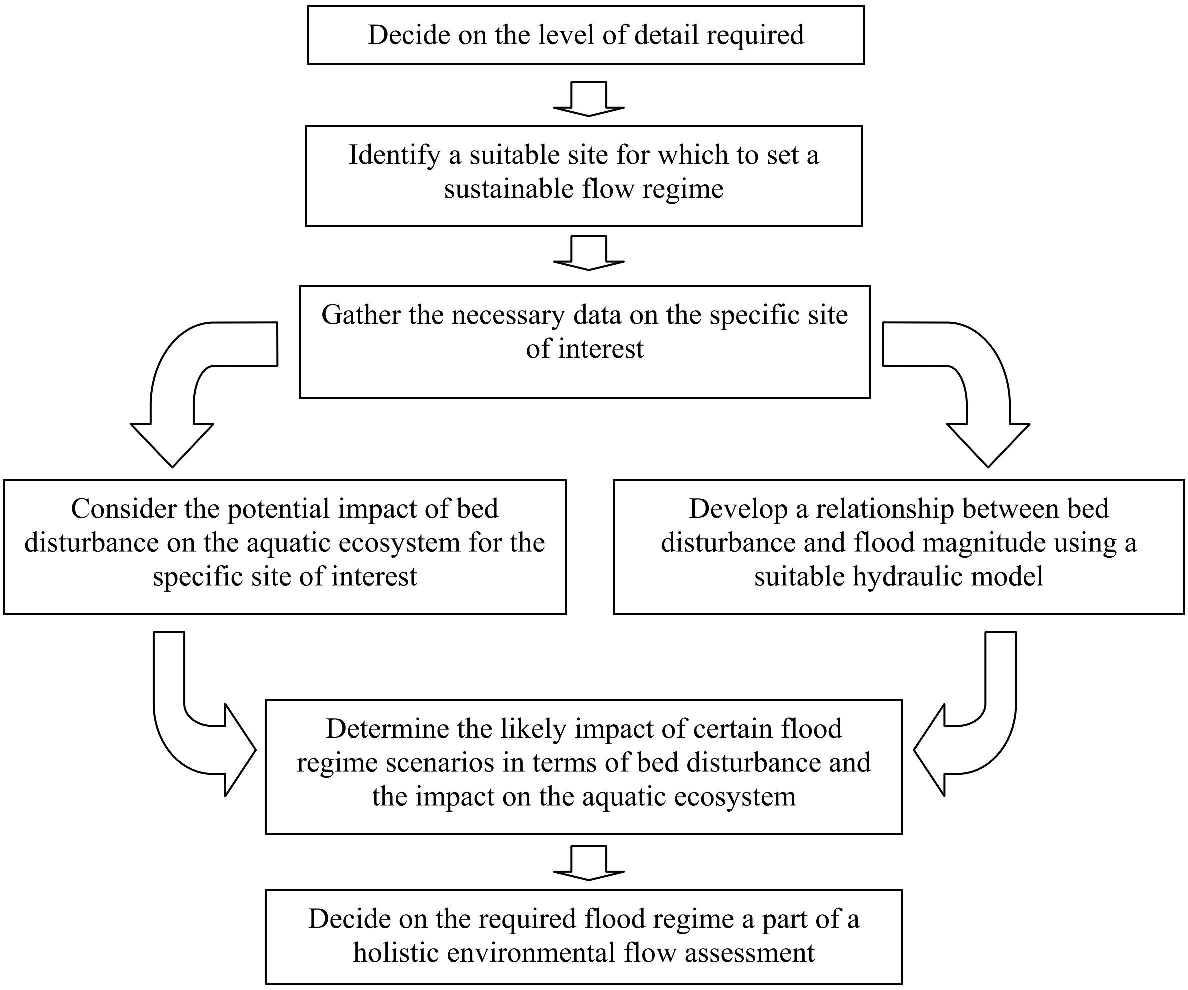
- Large, but regularly occurring, intra-annual floods are associated with higher levels of population reductions and affect all stream invertebrates.
- Movement of substratum particles is not a threshold for disturbance-responses, since almost all taxa were reduced on unmoved as well as moved substrata.
- There is a wide difference in the relative refugium afforded to different taxa, as a result of some substrata remaining stable over a flood.
- Resistance to floods at a reach level is considerable, indicated by a 58% overall reduction in invertebrate density (or 42% survival) as a result of two floods that moved between 25 and 43% of the river bed particles, in all size classes.
- Resistance to floods may be exaggerated by the immigration of new individuals of some species, in the form of new recruits of small instars from the hyporheos or upstream reaches, which would constitute a resilience response to floods in these taxa.
- No direct relationship was found between invertebrate densities after a flood and the distribution of maximum forces acting on bed particles during the flood, measured as unit applied stream power, possibly as a result of micro-scale movements of invertebrate within or on the same substratum particle.

These results add to the current understanding of how floods may affect ecological processes regarding species interactions, since they clearly demonstrate substantial differences in the disturbance-response between different and potentially competing species. The preliminary species-specific results may aid in setting flow requirements in rivers, particularly where there is evidence of species interactions, or where pest species (e.g. Chironomidae, Simuliidae) may proliferate under low disturbance regimes.

Guidelines for the Determination of Substrate Maintenance Flows
Proposed guidelines for the determination of substrate maintenance flows have been developed and are presented in the Hydraulics Report. The proposed guidelines are intended for use in the DRIFT method of defining environmental water requirements, but they can also be applied to any other method. The proposed guidelines are summarised in **Figure 1**. The proposed guidelines draw on the findings of this Study in terms of recommendations for a suitable hydraulic model for predicting either the average level of bed disturbance based on DRIFT flood class. These could be used for a simple

intermediate level reserved determination study, or the more detailed model that predicts the movement of individual stones based on the critical ratio of applied power to required power, also known as the movability number. For a more detailed comprehensive reserve determination study, an understanding of the impact of particular floods on the movement of individual stones can be used in conjunction with an understanding of how stone movement impacts on the populations of particular key invertebrate species, to determine the suitability of a specific flood regime.

Figure 1: Proposed Guidelines for the determination of substrate maintenance flows in cobble and boulder bed rivers



It is important to note that the proposed guidelines are only preliminary in that they need to be considered in the light of the broader requirements for determining environmental water requirements for rivers.

Recommendations for Further Study

It is important to note that the models and guidelines presented in this Report are based on a limited sample of thirteen flood events in two rivers in the Western Cape. It is important that the recommendations made in these Reports are tested on other rivers and for other flood events, before they can be fully developed. These and other research recommendations with regards to the hydraulic model are listed below:

- Further investigations into reduction in transport capacity due to the presence of bed forms in cobble and boulder bedded rivers in addition to the influence of non-uniform bed material.

- A study of the equilibrium distribution of stone sizes in cobble and boulder bedded rivers with particular reference to the presence of bed forms such as clusters of larger stones with smaller stones located inside.

- Developing a better understanding of the mechanisms for energy dissipation in sheltered areas of the bed through detailed field observations and possible laboratory experiments and the impact that this will have on the incipient motion of stones in these sheltered hollows.

- Investigate ways of determining absolute bed roughness (k) and energy slope (s) at particular points where stones are located on the bed of cobble and boulder bed rivers.

- Analysis of the structure of stable bed forms to determine if these can be identified and quantified in a study reach and the relevance that this will have on determining the bed roughness and the amount of refugia available for stream ecology.

- Further study is required to confirm the proposed empirical relationship between the intensity of movement and the DRIFT flood class. In particular the use of the reach characteristic term (α) needs to be tested on other rivers.

It is important to note that the observational data on which this research was based, effectively represents only three replicates in what might be a highly variable set of responses to floods, dependent on not only the specifics of the flood hydrograph (peak and duration), but the timing of the season, initial population densities, and the like.

Seasonal and inter-annual differences in responses are likely to be considerable, and these need to be investigated to substantiate these results.

The relatively successful outcome of the hydraulic model developed to describe incipient motion, in terms of its ability to indicate the movement status of previously unmarked river stones, raises the potential for simpler studies on flood responses to be undertaken in the future, free from the complicating error effects of repeat-sampled stones. This will enable large sample sizes to be processed, with more robust results.

1. INTRODUCTION

1.1 Background

In cobble and bed rivers, many aquatic organisms are dependent on the channel bed for their survival. Depending on the species and life-cycle, the channel bed provides refuge from floods, shelter during droughts and from extreme temperatures as well as interstitial spaces in which to lay and incubate eggs. Sufficient flow through the interstitial spaces and regular disturbance of the substrate particles, allows the replenishment of nutrients and oxygen while metabolic wastes are continuously removed. In addition, the movement of cobbles provides a control on the growth of certain species to maintain a balanced aquatic ecosystem. Species differ in their substrate preferences and requirements and the suitability of substrate for colonization by aquatic fauna and flora depends on its particle size distribution, the size of interstitial spaces and degree of embeddedness. The channel bed of cobble and boulder bed rivers is often referred to as a “faunal reservoir”, as it provides the source for recolonisation of a stream if invertebrate populations are depleted by adverse conditions.

To ensure a healthy and biodiverse ecosystem in cobble and boulder bed rivers, it is imperative that the channel bed is maintained. In pristine catchments this is achieved by the range of flows characteristic of the natural flow regime, which typically incorporates “maintenance” flows of different timing, duration and frequency. The construction of dams however, leads to a change in the flow regime, the flooding magnitude and frequency as well as the sediment transport capacity in the river channel downstream. This has a definite, often negative, impact on the dynamics of substrate movement and maintenance, which in turn affects the biotic faunal and floral aquatic environment. In order to maintain a healthy and productive substrate environment in cobble and boulder bed rivers it is necessary that the environmental flow requirement for these rivers accommodate a “substrate maintenance flow component”. The availability of water, the cost of water that is released and which is lost for storage, as well as the financial implications associated with the installation of outlet structures at reservoirs, emphasize the need to specify substrate maintenance flows as accurately as possible.

The determination of a “substrate maintenance flow component” is complicated by various factors. Firstly, there is very little scientifically based data available regarding the impacts (both positive and negative) of different levels of substrate “disturbance” on the aquatic environment. Furthermore, it is necessary to contend with the complexity of flow and sediment transport processes in cobble and boulder bed rivers. This includes the effects of large scale roughness, macro scale bedforms, the heterogeneous nature of the substrate particles and the effects of “shielding” on critical conditions for sediment movement. In order to facilitate the specification of “substrate maintenance flows” in cobble and boulder bed rivers, which can be incorporated into either an environmental flow requirement or river rehabilitation programmes, knowledge of the relationships between substrate disturbance, the aquatic environment and discharge is critical.

1.2 Aims and Objectives

The objective of this research project has been to lay the foundation for the development of guidelines for the determination of substrate maintenance flow requirements to ensure the sustainability of cobble and boulder bed river ecosystems. The specific aims required to attain this objective are addressed in terms of the following deliverables:

1. Develop a theoretically based hydraulic model that will address the relationship between discharge and substrate disturbance in cobble and boulder bed rivers.

2. Define and quantify ecologically significant substrate disturbance levels in cobble and boulder bed rivers.

3. Develop guidelines for the specification of substrate maintenance flow components in cobble and boulder bed rivers.

The above deliverables have been met through the preparation of two reports entitled:

- *The Development of a Hydraulic Model for Determining Bed Disturbance Due to Floods in Cobble and Boulder Bed Rivers (WRC Report No 1411/1/07)*
- *Flood Disturbance Responses of Invertebrate Assemblages in Two Cobble and Boulder Bed Rivers of the Western Cape (WRC Report No 1411/2/07)*

This Report, the first of the two, is referred to as the *Hydraulics Report*. This Report relates primarily to the first of these three aims and describes the mathematical hydraulic model developed to describe the factors relating to the onset of incipient motion. A second report, published separately, referred to as the *Ecological Disturbance Report*, addresses the findings in regards to the second of the three aims.

Due to limited data available for determining the ecological disturbance levels, it was decided not to produce a third report giving guidelines for the development of substrate maintenance flows, as it was felt that there is still a substantial amount of work that needs to be done on the impact of specified flood events on aquatic organisms. Preliminary guidelines on determining the level of bed disturbance using the proposed hydraulic model for incipient motion in cobble and boulder bed rivers have been developed along with a proposal for how the ecological disturbance levels could be determined with some initial indications based on the findings of this study. These preliminary guidelines are included in this Report on the hydraulic model.

1.3 Report Format

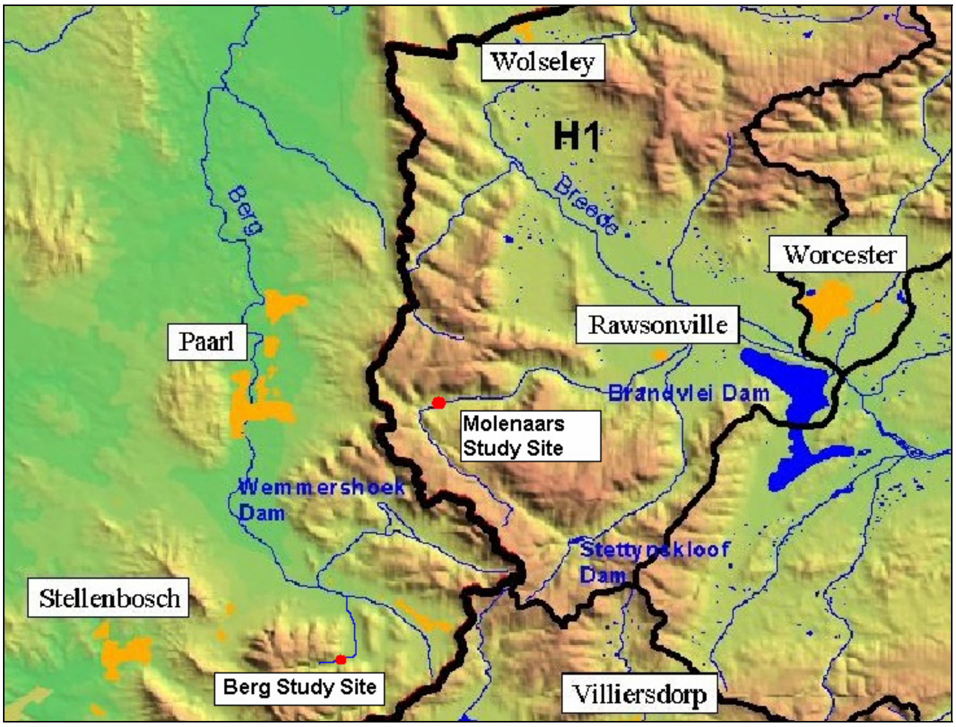
The following section of this Report will describe the methodology employed to collect the necessary data as well as give a description of the flood events that were analysed. Following this there is a literature review which looks at the current state of knowledge in terms of incipient motion and substrate bed disturbance which forms the foundation of the analytical approach adopted. The analysis of the results is described in **Section 4**. This consists of the development of a relationship between the DRIFT flood class and the level of disturbance as well as a description of the proposed theoretical model for understanding the results of this study, in terms of the criteria for incipient motion in cobble and boulder bedded rivers. This is followed by the proposed preliminary guidelines for determining substrate maintenance flows in cobble and boulder bed rivers. The final section of this Report presents a few conclusions emanating from the project and makes some recommendations for further work.

2. DATA COLLECTION

2.1 Site Selection

The two study sites selected for this project are shown in **Figure 1**. Both study sites are located in mountain catchments in the Western Cape. Both rivers have their origin in the same mountain range and the two study sites are located within 50 km of each other, but in different catchments. This area of the country is characterized by significant amounts of rainfall (over 1000 mm per annum) that usually occur as intense storm events during the winter months.

Figure 1: Location of Study Sites



Both sites are located in the headwaters of the Cape Fold Mountains and are characterized by short, but intense flood events, relatively steep gradients, and bed particles predominantly derived from the Table Mountain group sandstones in the cobble to boulder bed range, as defined by the Wentworth scale in **Table 1**.

The first study site is located on the Molenaars River. This river is one of the main tributaries of the Breede River, which is the largest river in the Western Cape and which flows into the Indian Ocean. The study reach has relatively well defined banks on both sides and consists primarily of a riffle and rapid section ending in a large pool. The layout of the Molenaars River study site as well as the Thalweg profile and a selection of cross-sections, and the stone size distribution are shown in **Appendix A1**.

Table 1: Classification of bed particle sizes (adapted from Brakensiek et al., 1979)

Class (Wentworth)	Diameter (mm)
Boulder	>256
Cobble	64 to 256
Gravel	2 to 64
Sand	0.0625 to 2
Silt	0.0039 to 0.0625
Clay	< 0.0039

Figure 2: Molenaars Study Site

The second study site is located in the headwaters of the Berg River, which is the second largest River in the Western Cape and flows into the Atlantic Ocean.

Figure 3: Berg River Study Site

The study site is located on a slight bend in the river and has a steep bank on the outside (left hand) bank and a lateral bar of deposited cobbles on the inside bank. A small rapid section dominates the top half of the site leading to a deeper pool in the lower half of the reach.

The layout of the Berg River study site as well as the Thalweg profile and a selection of cross-sections and the stone size distribution is shown in **Appendix A2**.

2.2 Site Set-up

A detailed survey of both study sites was performed based on thirty transects across each selected study site reach. Transects were placed at 2 m intervals and the bed level was surveyed at 1m intervals along each transect. In addition, a detailed digital terrain model of the Molenaars study site was developed using aerial photogramatic survey of the study area prior to the initial set-up and this was deemed to be accurate within 10 cm. The thirty transects were marked by steel pegs on each bank of the river and the stones to be studied were selected by stringing a tape between the pegs and selecting stones at two meter intervals across each transect. In total 345 and 435 stones were selected at the Molenaars and Berg River study sites respectively.

The selected stones were marked and numbered with paint, putty or a waterproof pen. Initially small magnets were attached to some of the stones as it was felt that this would have less of an impact on the potential for organisms to recolonise a marked stone than a paint or ink mark. It was, however, found that there was too much natural magnetism in the rocks to make this a reliable method for locating stones after a flood and it was thus abandoned. If possible the stones were removed from the bed and measured in terms of their three main axes. Invertebrate and periphyton samples were taken and the stones were replaced in their original positions. If the stones could not be removed then their visible dimensions were measured. Both the top and the bottom of the stones were marked to make it possible to determine if the stone had been turned over during a flood event, without it necessarily being moved from its original location.

Eight clear plastic pipes, 2 m long, were placed at intervals along both bank of the study reach to be used to measure the water level during a flood. The pipes were attached to metal y-sections that were securely driven into the ground. The plastic pipes had holes drilled in the bottom and the top to let water in and air out. Sawdust or cork flakes were placed in each pipe and after a flood the level of the ring of cork flakes stuck to the inside of the pipe was measured as the highest water level reached under the relevant flood. The inside of the pipe was then washed clean and the cork flakes replaced ready for the next flood.

Figure 4: Study Site Set-up

Figure 5: Example of a marked stone

Figure 6: Plastic Stage Pipe used to Measure Flood Levels

2.3 Base Flow Conditions

During the study site set-up, base flow conditions were measured in terms of both hydraulic and ecological characteristics. Both sites were established at the start of the winter flood season under assumed winter base-flow conditions rather than summer low-flow conditions. The depth and average velocity were recorded above each of the marked stones. Invertebrate samples and periphyton samples were taken for a number of the marked stones. After sampling, the stones were returned to their original positions in the bed.

The hydraulic base flow conditions in terms of stone size, depth, velocity, Froude number, Reynolds number, stream power and bed shear stress are shown in **Appendix B1** for the Molenaars site and **Appendix B2** for the Berg site. The base flow water level profiles for both sites are also given.

Figure 7: Taking a Periphyton Sample

Figure 8: The Molenaars Study Site in Flood

2.4 Flood Event Data

The first set of flood event data was collected at the Molenaars study site during the winter of 2003. Six flood events were recorded during this period. During the winter of 2004, flood event data was collected for five floods at both the Molenaars and Berg study sites.

For the determining of environmental flow requirements the floods were classified according to the DRIFT methodology (King *et al.*, 2004). DRIFT stands for Downstream Response to Imposed Flow Transformations. It is a scenario-based methodology for environmental flow assessments that requires a range of experts to assess the potential impact of a specified flow regime on the aquatic and riparian environment. DRIFT separates the long-term average daily flow data into eight flood classes. Classes 5 to 8 represent the inter-annual flood events with a return period of between two and fifty years. Classes 1 to 4 represent the intra-annual flood events. The magnitude of these floods is obtained simply by halving the two-year return period flood to obtain the Class 4 flood which is halved again to obtain the Class 3 flood, and so on.

The eight flood classes for the two gauges immediately downstream of the study sites have already been determined by Howard (2004) for G1H004 on the Berg River and Brown and King (2002) for H1H018 on the Molenaars River and these are shown in **Table 2**. Howard (2004) noted that there was some concern about the reliability of the flow record for G1H004 prior to 1980. For this reason flood classifications were determined based on both the full record and a shorter record after 1980. For the purpose of classifying the floods studied during this project, the classification based on the shorter record was used. This is based on the greater level of accuracy of the flow record after 1980, but introduces a higher level of uncertainty, particularly with regards to the longer return period floods.

Table 2: DRIFT Classification based on Average Daily Flows (m^3/s)

Class	Recurrence Interval	H1H018 (Molenaars)	G1H004 (Berg) (Short Record)	G1H004 (Berg) (Long Record)
I	Intra annual floods	5.0	3.6	4.3
II		16.0	7.2	9.5
III		31.0	14.5	19.1
IV		61.0	29.0	38.2
V	1 : 2 years	93.7	58.7	76.3
VI	1 : 5 years	146.0	75.3	118.0
VII	1 : 10 years	181.0	78.8	154.6
VIII	1 : 20 years	187.0	85.6	178.0

The flood events for which stone movement data were recorded are shown in **Figure 9**, **Figure 10** and **Figure 11**. These figures show the average daily flow recorded at the two gauges G1H004 and H1H018 located immediately downstream of the Berg and Molenaars study sites, respectively. The DRIFT flood classification levels are also shown.

Figure 9: Flood Events Observed on the Molenaars River (H1H018) in 2003

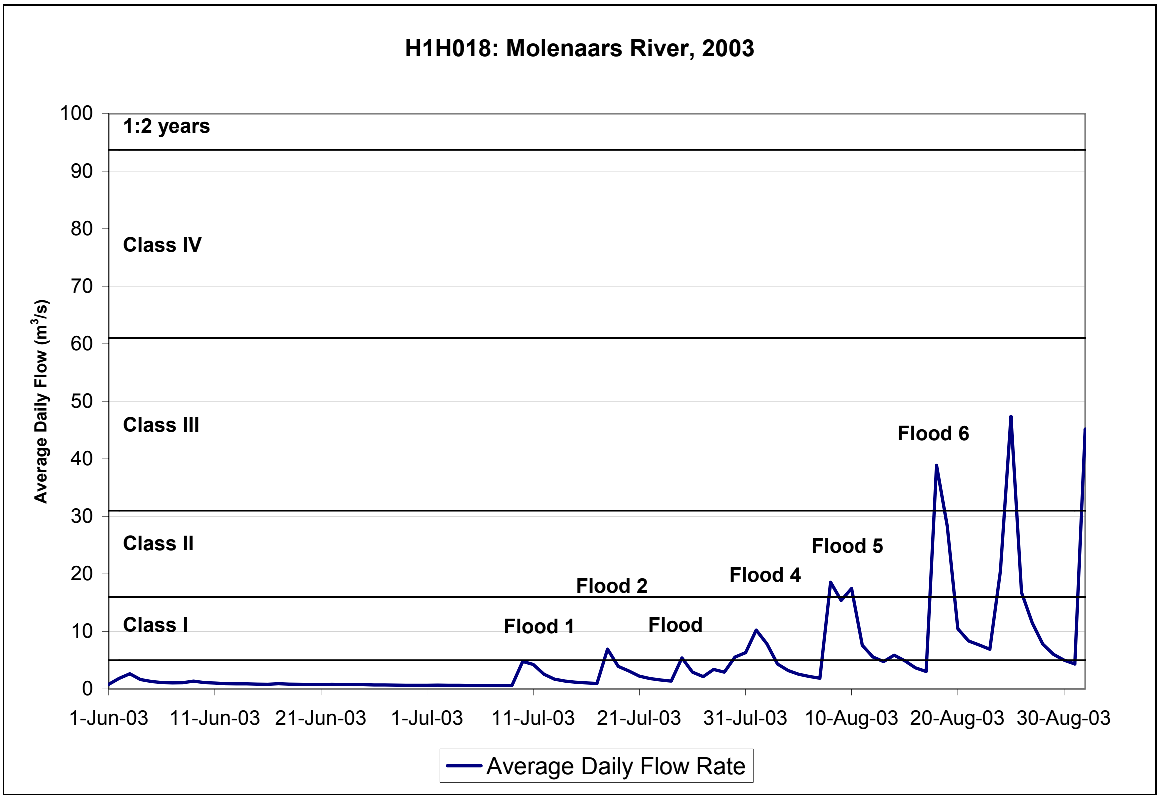


Figure 10: Flood Events Observed on the Molenaars River (H1H018) in 2004

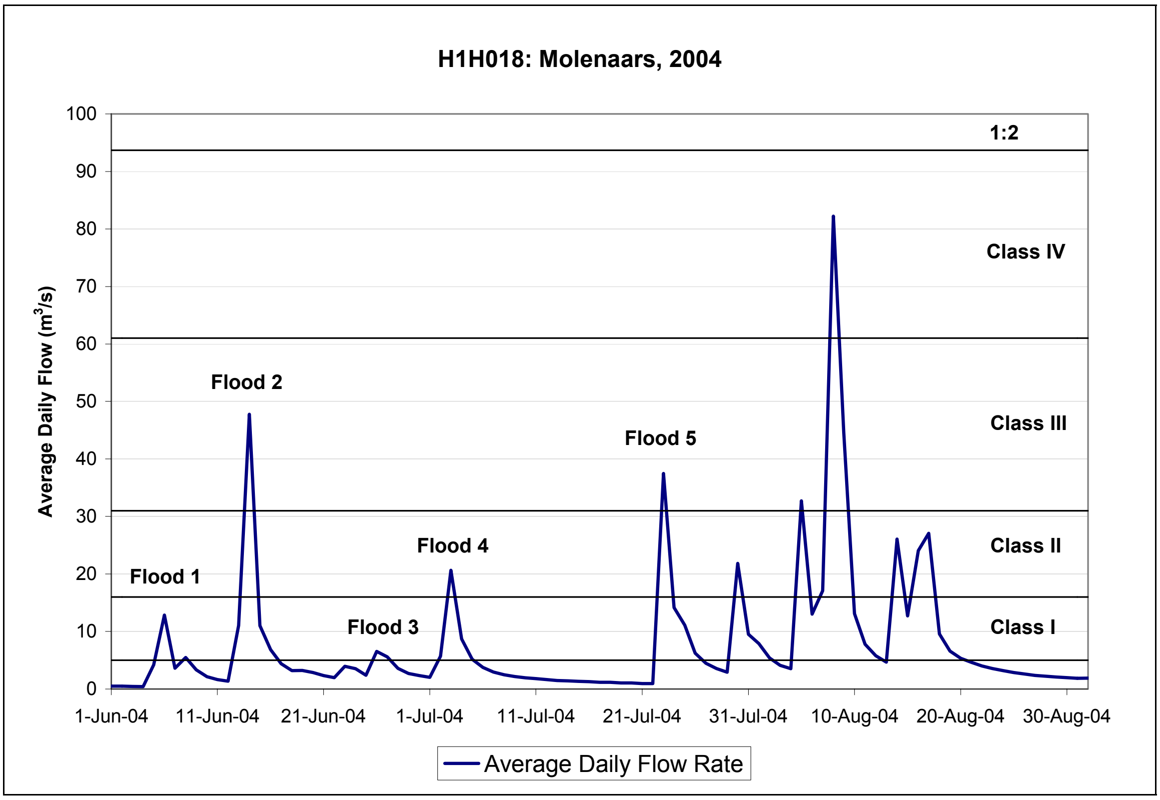
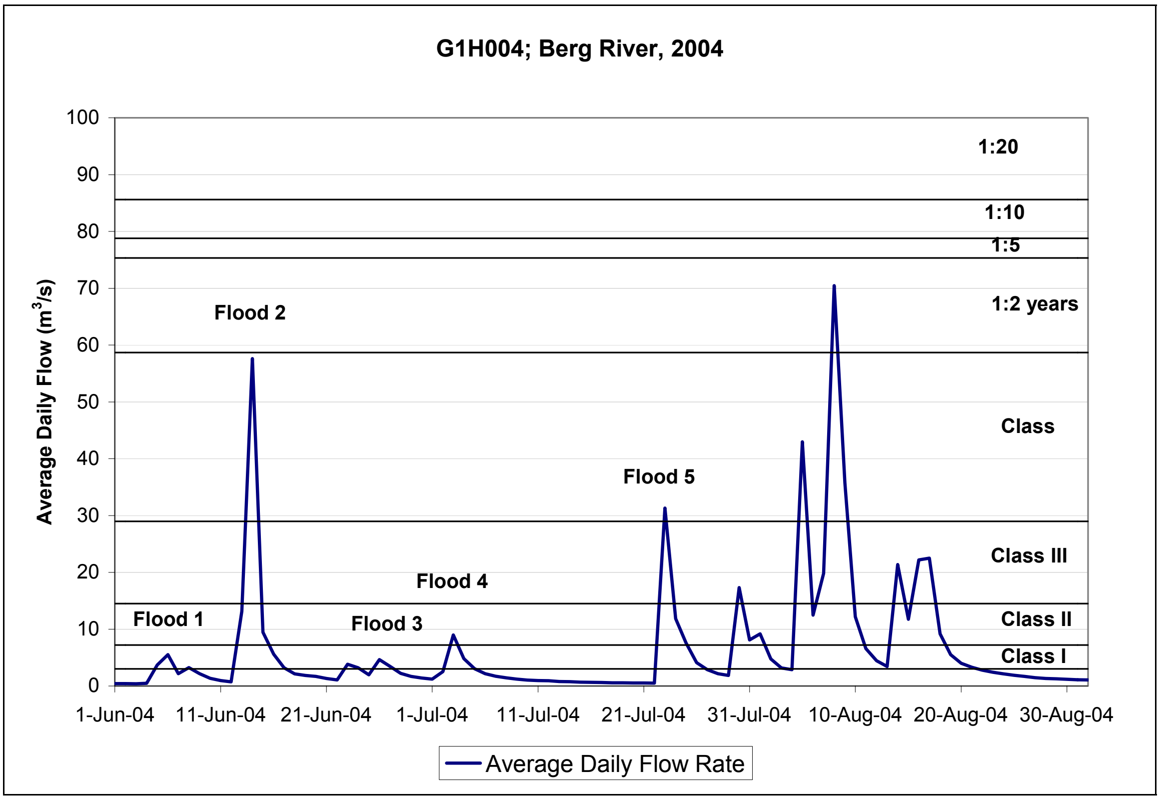


Figure 11: Flood Events Observed on the Berg River (G1H004) in 2004



The maximum flow experienced at the study reach during each flood event was estimated by reducing the instantaneous flood peak observed at the downstream gauge by the ratio of the catchment area upstream of the study site to the catchment area upstream of the gauge[1]. The estimated maximum flow rate, average daily flow rate, flood volume (including base flow) and class of flood as determined by the average daily flow rate at the downstream gauge for all the observed flood events are given in **Table 3** and **Table 4**.

The maximum water level for each flood event was recorded by measuring the height of the cork or sawdust ring left on the inside of the plastic pipes. By comparing this to the surveyed heights of the pipes, it was possible to calculate an average water level profile for the study reach. This was used to measure the water slope during the flood as well as the depth above each sampled stone. The water surface profiles for the observed flood events are given in **Figure 12**, **Figure 13**, and **Figure 14**.

[1] The ratio of catchment areas for the Molenaars study site was 88 km^2/113 km^2 = 0.78 and for the Berg study site was 41 km^2/72 km^2 = 0.56.

Table 3: Flood events observed at the Molenaars Study Site

Year	Event Number	Date	Duration (hours)	Max Flow (m^3/s)	Avg. Daily Flow (m^3/s)	Volume (Mm^3)	DRIFT Class
2003	1	10th July	33	5.56	3.72	0.41	I
	2	18th July	21	15.23	5.41	0.49	I
	3	25th July	14	8.60	4.20	0.28	I
	4	1st August	26	28.76	7.98	0.95	I
	5	8th August	26	36.46	14.45	1.74	II
	6	18th August	32	140.80	30.29	4.15	III
2004	1	6th June	29	20.20	10.02	1.04	I
	2	14th June	33	140.97	37.21	3.82	III
	3	26th June	31	8.87	5.13	0.66	I
	4	3rd July	21	46.38	16.08	1.35	II
	5	23rd July	18	113.93	29.17	2.67	III

Table 4: Flood events observed at the Berg Study Site

Year	Event Number	Date	Duration (hours)	Max Flow (m^3/s)	Avg. Daily Flow (m^3/s)	Volume (Mm^3)	DRIFT Class
2004	1	5th June	28	7.27	2.08	0.40	I
	2	14th June	44	84.51	32.58	3.48	IV
	3	26th June	27	4.82	2.62	0.29	I
	4	3rd July	24	11.74	5.68	0.44	II
	5	23rd July	20	60.98	17.70	1.66	IV

Figure 12: Water Level Profiles for Molenaars Study site: 2003 Floods

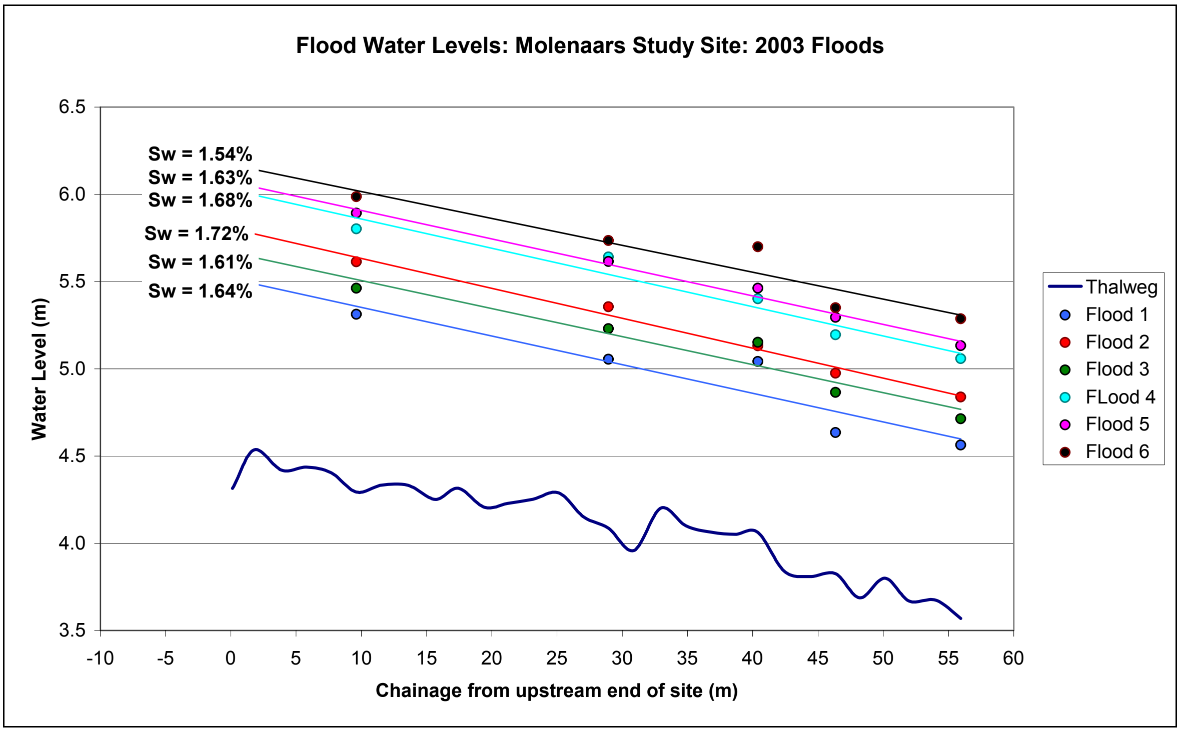


Figure 13: Water Level Profiles for the Molenaars Study Site: 2004 Floods

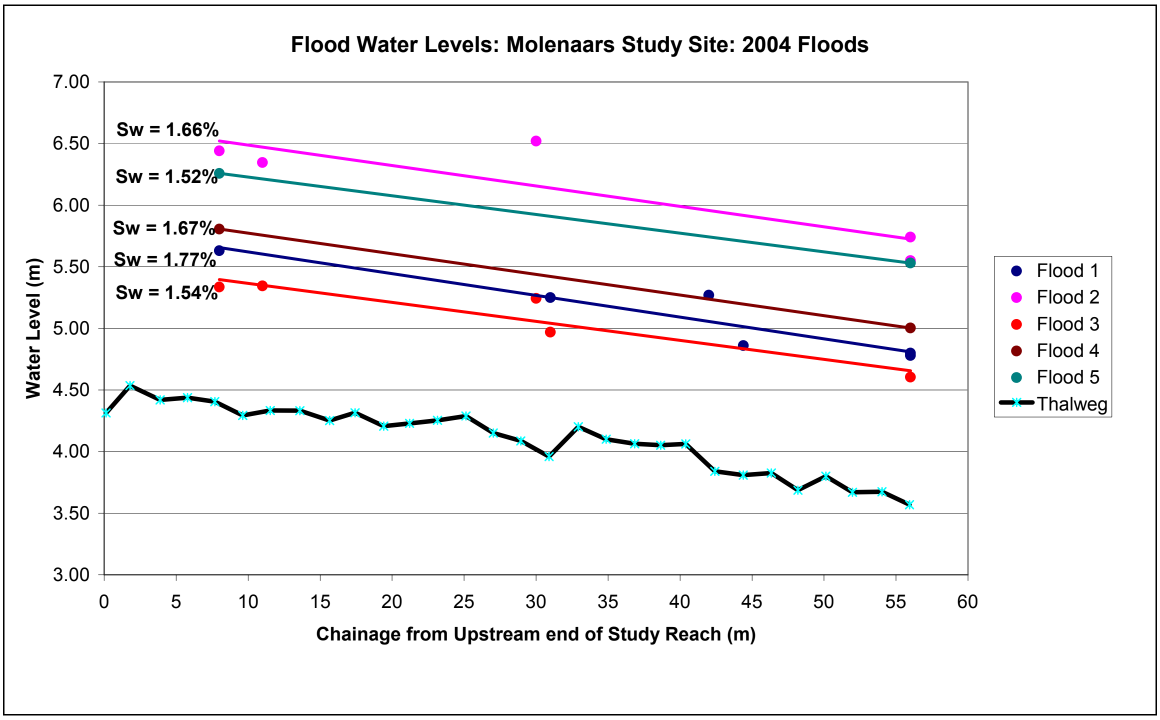
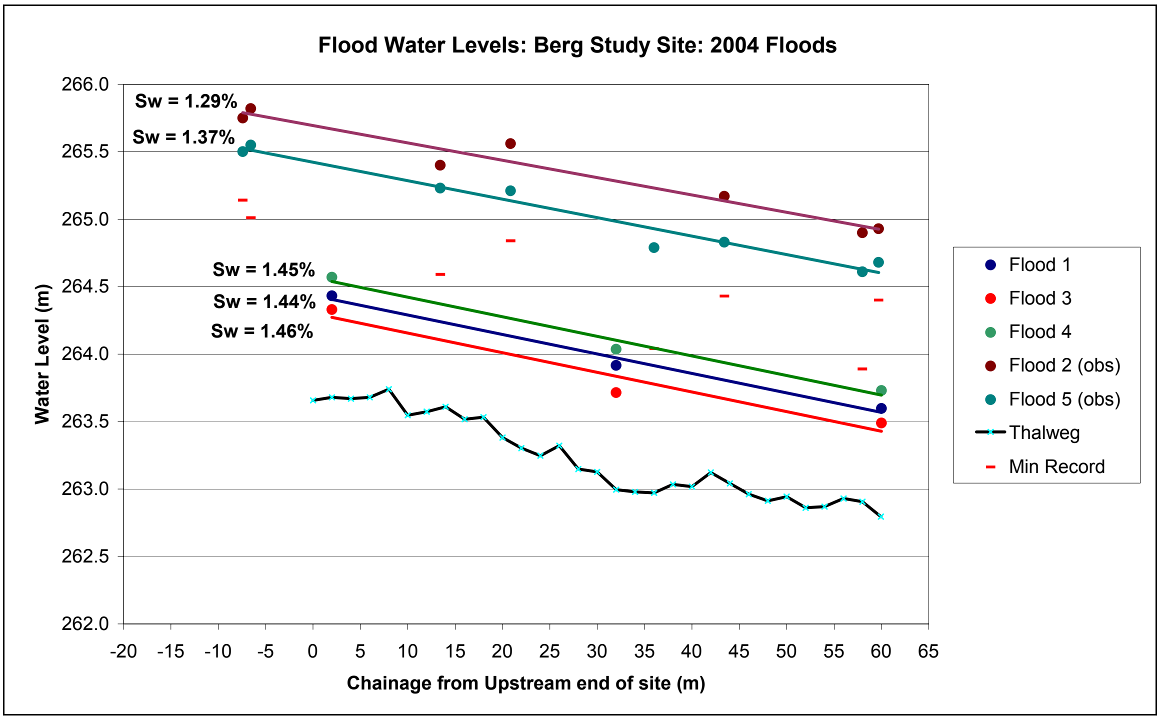


Figure 14: Water Level Profiles for the Berg Study Site: 2004 Floods



It must be noted that the surface profile for Flood 6 in 2003 on the Molenaars was considered to be too low. This was based on a comparison with the profile for Flood 2 in 2004, which was of a similar magnitude. The water levels for Flood 6 had been estimated visually during the flood as the marks left by the cork were not clearly defined. It was assumed that this was the peak of the flood, but compared with the recorded levels for Flood 2, when the cork did leave clearer marks, it was decided that the water profile for this flood should be applied to Flood 6 of 2003, as well. The depths and average water slope for Flood 6 of 2003 were thus calculated based on this observation. There was also a problem with the observation of the levels of Floods 1, 3 and 4 for the Berg site. This was because the flood levels were below the minimum level that could be recorded on the stage pipes. The level of these floods had to be estimated based on Jonker's (2002) equation for calculating the water depth in cobble and boulder bedded rivers under conditions of medium to large-scale roughness.

2.5 Collection of Incipient Motion Data

After each flood event the study sites were revisited and the marked stones were located wherever possible. The movement of a particular stone was noted either in terms of whether it had simply been turned over or had been moved out of position. In the latter case, the distance that it had been moved was recorded. Stones that had been turned over or moved were replaced in their original locations ready for the next flood event. After some of the larger flood events a number of the marked stones could not be located.

They were assumed to have been washed out of the study site reach and were replaced by equivalent stones[2]. The dimensions of the new stones were recorded and used for the analysis of subsequent flood events.

The field notes for the initial site set up and from each of the visits to locate moved stones are included in **Appendix C** and the locations of the stones that moved during each flood are given in **Appendix D**. A summary of the stone movements by stone size class is given in the **Figures** and **Tables** below[3].

Table 5: Stone Movements in the Molenaars River during 2003 Flood Events

Intensity of Movement: Molenaars 2003							
Stone Size Classification		**Total**	**G**	**SC**	**LC**	**SB**	**LB**
Max size in class (mm)			64	161	256	514	1000
Total Number of Stones		344	4	91	73	111	65
Flood 1	Moved Stones	0	0	0	0	0	0
	Movement %	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Flood 2	Moved Stones	7	0	7	0	0	0
	Movement %	2.0%	0.0%	7.7%	0.0%	0.0%	0.0%
Flood 3	Moved Stones	2	0	1	1	0	0
	Movement %	0.6%	0.0%	1.1%	1.4%	0.0%	0.0%
Flood 4	Moved Stones	10	0	6	4	0	0
	Movement %	2.9%	0.0%	6.6%	5.5%	0.0%	0.0%
Flood 5	Moved Stones	26	1	18	4	3	0
	Movement %	7.6%	25.0%	19.8%	5.5%	2.7%	0.0%
Flood 6	Moved Stones	115	4	65	29	16	1
	Movement %	33.4%	100.0%	71.4%	39.7%	14.4%	1.5%

[2] While a concerted effort was made to find the stones after each flood event, there is a possibility that some of the stones assumed to have been washed out of the reach, may have instead been covered by other stones.

[3] Note that the standard classification of stone sizes into gravel (G), cobble (C) and boulder (B), have been further divided into small cobble (SC), large cobble (LC), small boulder (SB) and large boulder (LB). The maximum stone size in each class is indicated in the tables.

Table 6: Stone Movement in the Molenaars River during 2004 Flood Events

Intensity of Movement: Molenaars 2004							
Stone Size Classification		**Total**	**G**	**SC**	**LC**	**SB**	**LB**
Max size in class (mm)			64	161	256	514	1000
Total Number of Stones		343	5	60	73	136	69
Flood 1	Moved Stones	3	1	2	0	0	0
	Movement %	0.9%	20.0%	3.3%	0.0%	0.0%	0.0%
Flood 2	Moved Stones	78	4	41	20	13	0
	Movement %	22.7%	80.0%	68.3%	27.4%	9.6%	0.0%
Flood 3	Moved Stones	7	0	6	1	0	0
	Movement %	2.0%	0.0%	10.0%	1.4%	0.0%	0.0%
Flood 4	Moved Stones	15	1	7	2	5	0
	Movement %	4.4%	20.0%	11.7%	2.7%	3.7%	0.0%
Flood 5	Moved Stones	83	2	39	23	17	2
	Movement %	24.2%	40.0%	65.0%	31.5%	12.5%	2.9%

Table 7: Stone Movement in the Berg River during 2004 flood events

Intensity of Movement: Berg 2004							
Stone Size Classification		**Total**	**G**	**SC**	**LC**	**SB**	**LB**
Max size in class (mm)			64	161	256	514	1000
Total Number of Stones		432	27	120	92	139	54
Flood 1	Moved Stones	1	1	0	0	0	0
	Movement %	0.2%	3.7%	0.0%	0.0%	0.0%	0.0%
Flood 2	Moved Stones	187	26	92	44	24	1
	Movement %	43.3%	96.3%	76.7%	47.8%	17.3%	1.9%
Flood 3	Moved Stones	10	2	3	3	2	0
	Movement %	2.3%	7.4%	2.5%	3.3%	1.4%	0.0%
Flood 4	Moved Stones	7	1	4	2	0	0
	Movement %	1.6%	3.7%	3.3%	2.2%	0.0%	0.0%
Flood 5	Moved Stones	111	10	58	28	14	1
	Movement %	25.7%	37.0%	48.3%	30.4%	10.1%	1.9%

Figure 15: Levels of Disturbance in the Molenaars River during 2003 Flood Events

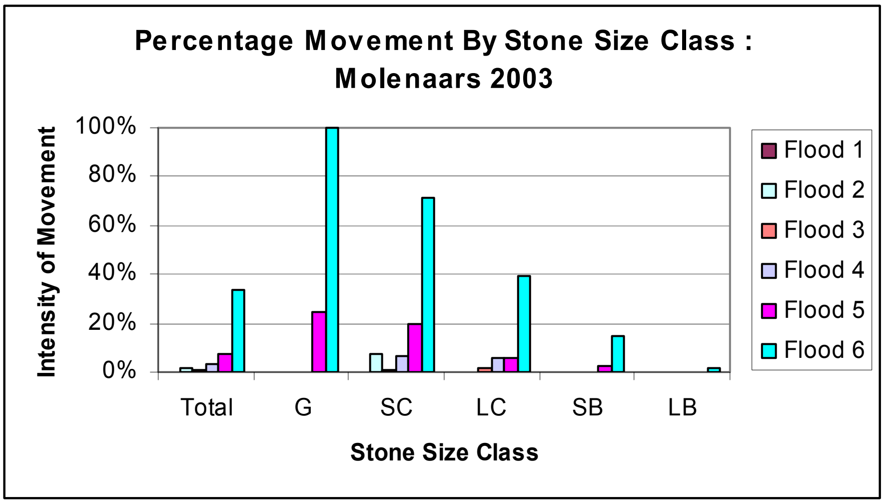


Figure 16: Levels of Disturbance in the Molenaars River during 2004 flood events

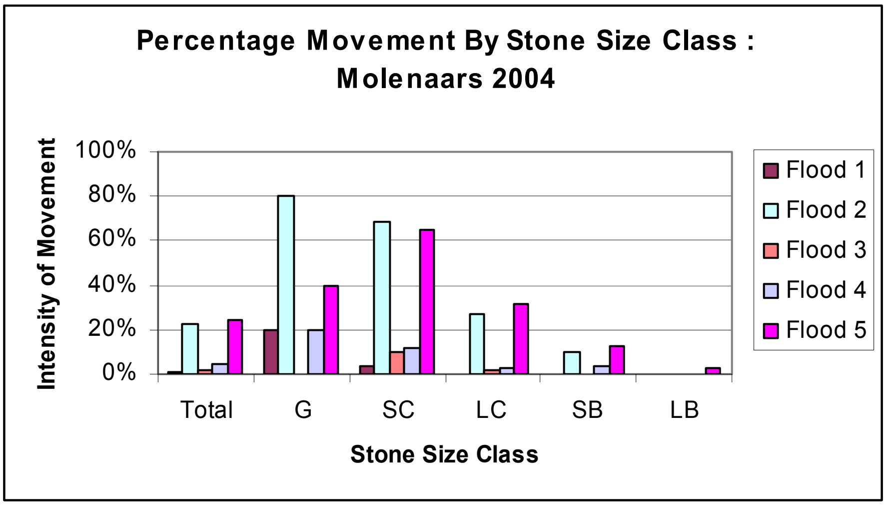
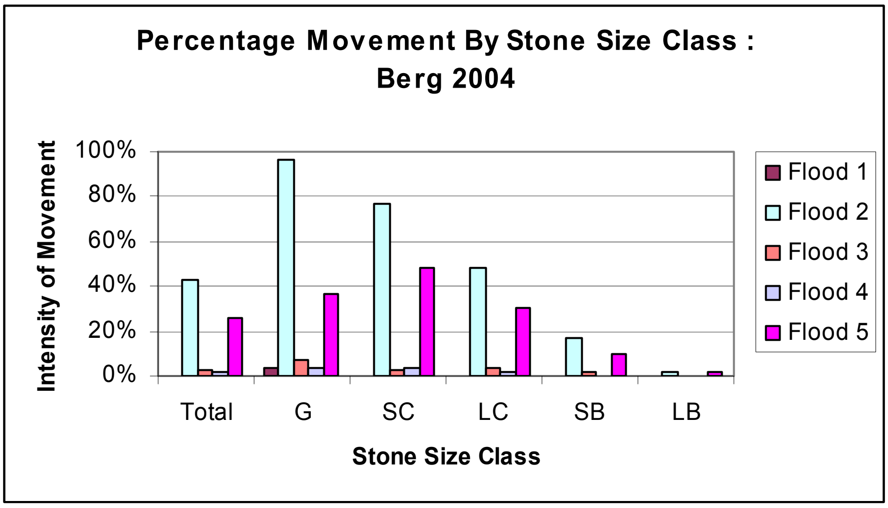


Figure 17: Levels of Disturbance in the Berg River during 2003 flood events



3. LITERATURE REVIEW

3.1 Ecological Significance

One of the central themes in aquatic ecology is the distribution patterns of lotic organisms and the driving factors that determine these patterns. Spatial patterns (and patchiness) of invertebrate distribution partly reflect the layering of temporal dynamics on environmental gradients (Ward, 1998). More recently, the emphasis has shifted to giving non-equilibrium and stochastic forces more importance as agents of community structure (Townsend, 1989). Central to this field of investigation is the notion of disturbance, and the idea that, in fact, some communities may not ever reach an equilibrium state.

Lake (2000) describes three categories of disturbance. Floods represent the major form of natural "pulse" disturbance in lotic ecosystems, whilst "press" disturbances refer to the acute change that is maintained (e.g. sediment load change as a result of landslides; many anthropogenic impacts) and ramp disturbances are described as "creeping" change (e.g. drought, alien invasion). Furthermore he argued that most definitions of disturbance confuse the biological response to a disturbance with the event itself, and proposed a narrower definition of disturbance as the application of "potentially damaging forces to habitat space occupied by a population, community or ecosystem ... [the magnitude of which] may be such that organisms may be killed or displaced, consumable resources may be depleted and habitat structure may be degraded or destroyed".

The critical difference in the above definition is the identification of a *potential* impact as a result of the application of a force. A definition of disturbance that is contingent on the biota being adversely affected (for example, the "opening up of space" in the definitions of Resh *et al.* (1988) and Townsend (1989) which explicitly implies mortality or displacement of biota) would preclude the possibility (at least hypothetically) that some biotas may be perfectly resistant to a disturbance and that their populations remain intact over the course of an event characterised by "the application of a force", as per Lake's (2000) definition of disturbance (e.g. Lancaster, 1999; Lake, 2000).

Lancaster (1999) described disturbance as a "response phenomenon", with responses being species specific, so that "whether a species perceives an environmental event as a disturbance will also be species specific". This laboratory study demonstrated variable responses by three taxa to increasing flow, these being either:

a) disturbance resistance (e.g. through physical attributes, such as clinging by hooks and claws)
b) changes in microdistribution (e.g. physical walking down a velocity gradient and/or accumulation in flow refugia).

According to this definition of disturbance, species that show disturbance resistance (no net loss or movement of individuals) will not have perceived the increase in flow forces as a disturbance. This description, whilst introducing a finer focus in the study of variable biological responses to disturbance, would require quantification of the response to environmental events before these may be pronounced “disturbance events”. Further, the definition of disturbance will become increasingly complicated if it may be simultaneously classified as both a disturbance event and a non-disturbance. In addition, the concept of resistance defines species attributes (e.g. resistance traits) in relation to disturbance, rather than as a definition of disturbance.

On the other hand, if disturbance is not to be species-specific by definition, the identification of what constitutes “a force acting on an area of streambed” reintroduces ambiguity into the definition of disturbance, particularly if the force does not necessarily need to result in any effect (it is only potentially damaging). Poff (1992) argued that a disturbance should be defined in terms of the physical event, but that the specification of a disturbance is scale dependent, and needs to be ecologically relevant to the question at hand. In other words, disturbance needs to be quantified both as a physical force and as a response event, where ecological response should be described at the same spatial or temporal scale.

In this regard, comparing the responses of biota to the same magnitude of forces (i.e. disturbances) that act directly upon substratum particles and their biota (e.g. shear stresses, applied power or particle movement) may be a better basis for developing an understanding of the mechanism by which a “disturbance event” elicits one or another biological response. Different thresholds in the magnitude of physical forces may represent different scales of disturbance, and may be accompanied by a variety of biological responses, including resistance, use of refugium and/or reductions in populations or biological fitness.

Floods perform a variety of roles in maintaining the integrity of lotic ecosystems. The high shear stresses developed during a flood; suspend sediments, move and redistribute bottom material, scour and abrade the streambed, remove plant material, move detritus, and kill, maim and displace biota. The immediate impact of floods is to deplete the biota of streams, but recovery is usually rapid and results in a healthier ecosystem due to the removal of waste products. The ability of ecosystems to recover from a flood event is dependent on the presence of refugia in or associated with the stream channel. Refugia are defined as places not subject to severe hydraulic stresses during disturbance events where there is a reduction in the density-independent mortality of benthic organisms (Lancaster and Hildrew, 1993). When a river becomes part of a managed flow regime it is important to find a suitable balance between the need for channel maintenance and disturbance of bed particles to remove waste products and the need to preserve refugia for benthic organisms to ensure a rapid recovery of the stream ecology. For this an improved understanding of the relationship between the hydraulic stresses experienced by benthic organisms and the criteria describing the incipient motion of the bed particle is essential in an understanding of the level of disturbance experienced by an organism and its ability to recover from this disturbance event.

3.2 Hydraulic Theories of Incipient Motion

Incipient motion defines the beginning of sediment movement. In other words, it encompasses all the factors involved at the threshold between non-movement and movement of a particle. A number of relationships have been proposed to link critical threshold parameters to the initial motion of a grain. The best known criteria are based on critical shear stress as originally developed by Shields (1936). In this section of the report, the Shields approach and others, as well as a promising alternative approach based on stream power, are discussed.

3.3 Critical Shear Stress

The retarding effect that limits the movement of one fluid element relative to another is traditionally represented by so called shear stress. This shear stress represents momentum exchange across the planes and can be derived from the equivalency between forces acting in the various planes and momentum exchange. Shear stress (τ) is calculated according to the following formula:

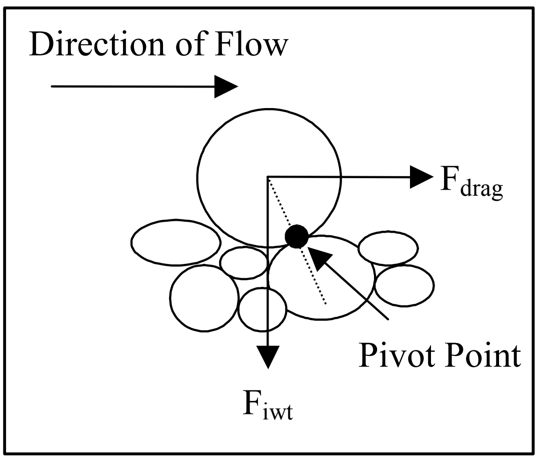
$$\tau = \rho g(D - y)s \tag{3.1}$$

where *D* : flow depth,
s : is the energy slope, and
y : the distance from the bed

From this equation it is easy to see that the maximum shear stress will prevail at the bed (i.e. when $y = 0$) and that this maximum shear stress applied at the bed will increase with *D* and *s* (i.e. with an increase in the size of the flood).

The onset of motion occurs when the shear stress along the bed (τ_0) exceeds some critical shear stress (τ_{crit}) at which point the moment of the drag force (F_{drag}) about the pivot point of the relevant particle exceeds that of the immersed weight force of the particle (F_{iwt}), as shown in **Figure 18**.

Figure 18: Schematic Representing the Forces Acting on a Particle on the Stream Bed



Shields (1936) showed that the particle entrainment was related to a form of Reynolds' Number (*Re*$_*$), based on the shear velocity:

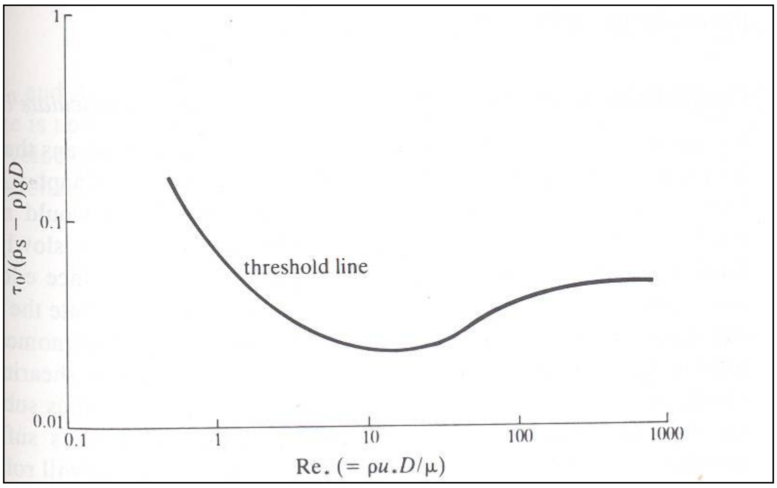
$$\mathrm{Re}_* = \rho u_* D / \mu \quad \text{with} \quad u^* = \sqrt{\tau_0 / \rho} \tag{3.2}$$

Shields developed a non-dimensional entrainment function that described the threshold of movement of particles in a uniform bed:

$$\theta_{crit} = \frac{\tau_{crit}}{(\rho_s - \rho) g d} \tag{3.3}$$

The value of θ_{crit} plotted against *Re*$_*$ is shown in **Figure 19**.

Figure 19: Shields' diagram



The Shield's entrainment function is a complex, non-dimensional variable dependent on the distributions of particle size, shape and packing, and needs to be assigned a critical value in order to solve the left-hand term of the equation for a given grain diameter or shear stress value. The Shields equation was originally tested in a flume using spheres of uniform size and the entrainment function was found to approach a constant value of 0.06 for course grained sediment with *d* > 6 mm (Shields, 1936; Bagnold, 1966; Allen, 1970).

In natural streams, however, there is a high variance in the estimated values of τ_{crit} as a result of the non-uniformity of substrata particles. According to Wiberg and Smith (1987), the surface of a poorly sorted bed can have critical shear stresses that differ significantly from the critical shear stress associated with that particle when placed on a well-sorted bed of the same size. They indicate that this difference is primarily due to the relative protrusion of the particle into the flow along with differences in the particle angle of repose, or bed pocket geometry that results from having a mixture of grain sizes on the bed. This led them to develop the graph shown in **Figure 20** (Wiberg and Smith, 1987), to determine the critical shear stress for a specific particle.

Figure 20: Calculation of Critical Shear as a Function of Particle Diameter

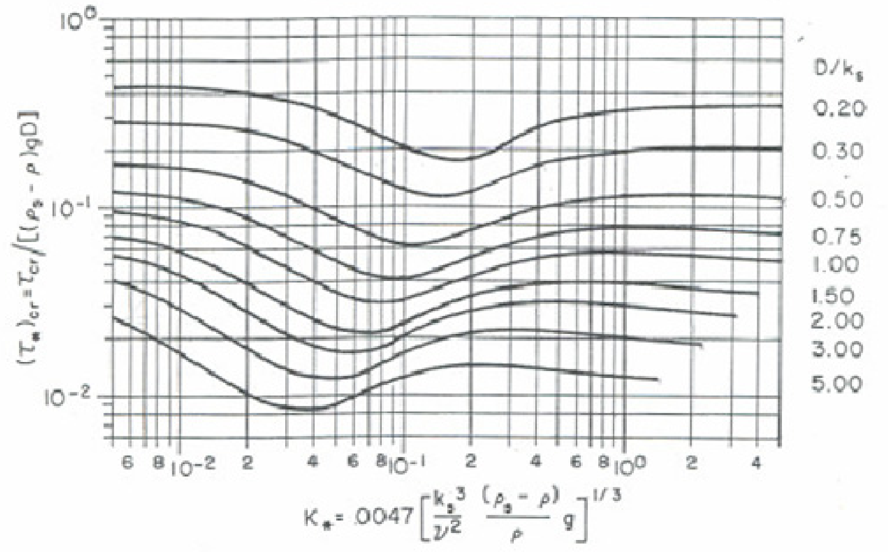


Fig. 13. Calculated nondimensional critical shear stress $(\tau_*)_{cr}$ as a function of the nondimensional particle diameter $K_* = 0.0047(\zeta_*)^{1/3}$ for values of particle diameter to bed roughness scale, D/k_s, from 0.2 to 5.0. The parameter K_* is defined such that it equals the bed roughness length k_s for sediment of specific gravity 2.65 in a fluid with a temperature of 10°C.

Wilcock & Southard (1988) found that the sorting of the mixture had little effect on the critical shear stress of individual fractions, once the median size (d_{50}) of the mixture and a fraction's relative size (d_i/d_{50}) are accounted for. Their data showed a consistent relationship between the critical shear stress of individual fractions and the fraction's relative grain size, despite a broad variation in the available data of mixture sorting, grain size distribution shape, mean grain size, and grain shape.

Investigation of threshold hydraulic conditions in gravel-bed rivers with naturally sorted bed material described by Andrews (1983) showed that the threshold shear stress τ^*_{ci} could be given by an equation of the type:

$$\tau^*_{ci} = a\left(\frac{d_i}{d_{50}}\right)^b \qquad (3.4)$$

This equation attempts to include the influence of pivoting angles by normalizing to respective mean diameters where the Shields factor (θ_c or τ^*_{ci}) varies, as a function of the relationship between the size of the surface particles involved (d_i) and the average diameter of the underlying material constituting the bed (d_{50}). In this type of equation, the coefficient, a, represents the Shields standard dimensionless coefficient (θ_c) for homogeneous sediment conditions, when (d_i/d_{50}) = 1. The (d_i/d_{50}) term attempts to provide a measurement of the hydraulic protection a stone of a certain diameter experiences due to its relative size to the bed. Several studies confirm the validity of this approach, even though the values of the coefficients differ vastly. **Table 8** (Petit, 1994) shows the coefficients derived for a number of these studies.

Table 8: Exponents Found to Describe Critical Shear Stress

A	*b*	d_{50}	d_i/d_{50} range	Study
0.088	-0.98	0.13-2.5	0.045-4.2	Parker *et al.* (1982)
0.083	-0.87	5.4-7.4	0.3-4.2	Andrews (1983)
0.045	-0.68	2	0.4-5.9	Milhous (1973) in Komar (1987)
0.045	-0.68	2	0.5-10	Carling (1983)
0.045	-0.71	0.75	0.67-5.33	Hammond *et al.* (1984)
0.089	-0.74	2.3-9.8	0.1-2	Ashworth and Ferguson (1989)
0.047	-0.88	7.3	0.04-1.2	Ferguson *et al.* (1989)
0.049	-0.69	1.8-3.2	0.15-3.12	Ashworth *et al.* (1992)

The difference in coefficients might be attributed to the fact that the size distributions for individual reaches respond uniquely to a given distribution of particles, packing and turbulence characteristic of flow (Komar & Carling, 1991).

Komar (1987) also showed that the variance in measured τ_c produced by the relationship of pivoting angles existing in mixed beds could be reduced if normalized to respective mean diameters. This led to the modification of the original Shields equation to derive the following flow competence equation:

$$\tau_c = 0.042(\rho_s - \rho)g.d_{50}^{0.6}.d_{max}^{0.4} \quad (3.5)$$

This equation is plotted in **Figure 21** along with the Shields equation for uniform-sized substrate and a number of the empirically derived power equations for critical shear stress. From this plot it is clear that the line representing critical conditions in a mixed bed lies below that for a uniform-sized bed, which implies that having a mixed bed actually lowers the required τ_{crit} (Lorang and Hauer, 2003).

Lorang and Hauer (2003), however, suggested that extending Komar's equation to higher gradient channels (S > 0.002) with particle diameters >>100 mm could result in substantial errors. They found that Komar's equation tended to overestimate τ_{crit} for cobble and boulder bed rivers by as much as an order of magnitude.

Figure 21: Comparison of Empirical Flow-competence Equations

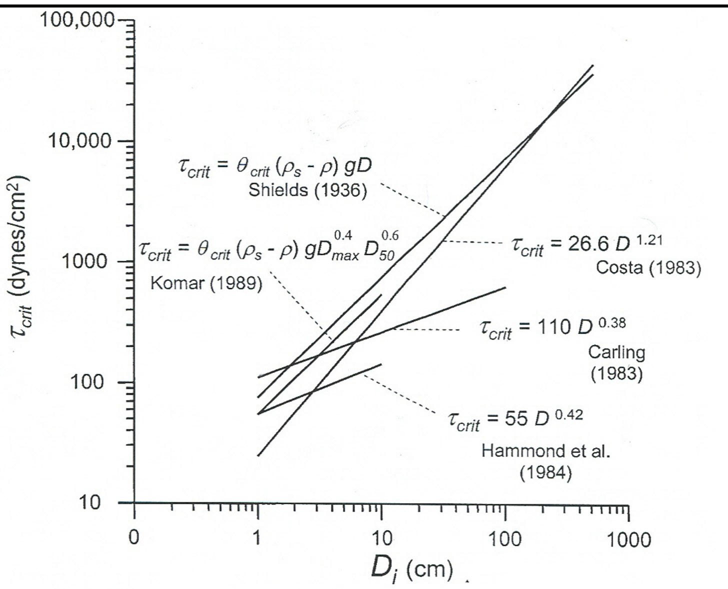


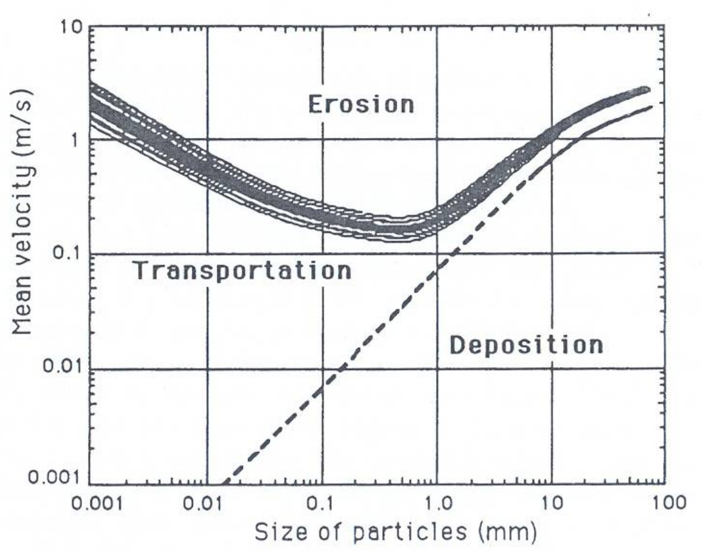
FIG. 3. Comparison of the empirical flow-competence equations of Costa (1983), Carling (1983), Hammond et al. (1984), the derived equations of Shields (1936), and the modified Shields equations (Komar 1989) (equations 15 and 18, see text). Lengths of the regression lines indicate the range of particle diameters included in each data set.

3.4 Critical Flow Velocity

Critical velocity is defined as the maximum velocity of the channel that will not cause erosion of the sediment forming the bed. Extensive empirical data exists relating maximum velocities to various soil and vegetation conditions. Hjulstrom (1939) developed the graph in **Figure 22**, which relates average critical velocity to particle size.

This simple method, however, does not consider the channel shape or flow depth. At the same mean velocity, channels of different shapes or depths may have quite different forces acting on the boundaries.

Figure 22: Hjulstrom Curves



3.5 Critical Flow Discharge

Bathurst (1987) argues that on steep slopes the critical conditions for movement are best predicted by an approach based on water discharge rather than the Shields shear stress. He therefore adopted the Schoklitch (1962) approach to prediction of critical flow conditions, based on water discharge rather than shear stress. Using flume data for bed materials with relatively uniform size distributions, he developed the empirical relationship:

$$q_{cr} = 0.15 g^{0.5} d^{1.5} S^{-1.12} \tag{3.6}$$

where q_{cr} : critical water discharge per unit width; and

S : bed slope

The equation was derived for the range of slopes 0.25<*s*<20% and particle sizes 3<*d*<44 mm and for ratios of depth to particle size as low as 1. The above equation was used in conjunction with the following equation to determine the critical flow condition for each particle size:

$$q_{ci} = q_{cr} (d_i / d_r)^b \quad \textit{with} \quad \mathrm{b} = 1.5(\mathrm{d}_{84}/\mathrm{d}_{16})^{-1} \quad \textit{and} \quad (\mathrm{d_r} = \mathrm{d}_{50}) \tag{3.7}$$

where q_{ci} : the critical unit discharge for movement of particle $\mathrm{d_i}$,

q_{cr} : the critical unit discharge for the reference particle size $\mathrm{d_r}$, and

b : an exponent.

3.6 Critical Froude Number

Aguirre-Pe *et al.* (2003) states that for ratios of flow depth to bed particle diameter less than ten, neither the Reynolds number of the solid loose particles at a stream bed nor the Shields parameter are adequate variables to predict critical flow conditions for the initiation of motion. A particle densimetric Froude number (F^*) is proposed as an alternative criterion to predict hydraulic conditions for the initiation of motion. This is given by the equation:

$$F^* = U / [(s-1)gd]^{1/2} \tag{3.8}$$

where U : mean velocity,

s : ratio of sediment and fluid densities,

g : acceleration due to gravity, and

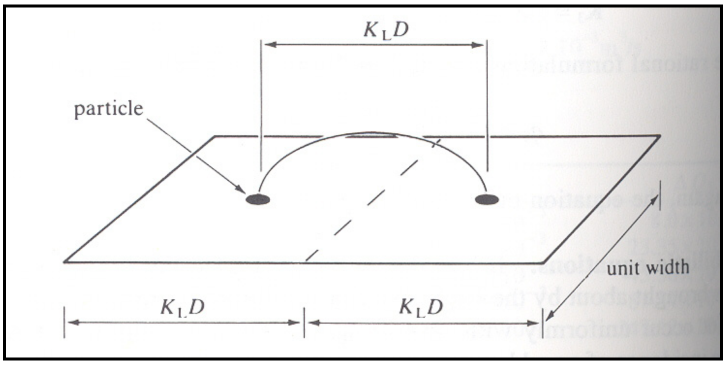
d : characteristic diameter of bed particle.

3.7 Probability models

Einstein (1942), in light of the fact that the incidence of an eddy capable of transporting a particular grain is some statistical function of time, proposed a probabilistic model of bedload for the case of even beds. Einstein's equation for the probability, *p*, that a grain will be eroded during the typical timescale, *T*, is given by (from Chadwick and Morfett, 1993):

$$p = f\{B_* \cdot \Psi\} \text{ with } B_* = \frac{K_v}{C_L K_A 135/2} \text{ and } \Psi = \frac{(\rho_s - \rho)D}{\rho R' S_0} \qquad (3.9)$$

Figure 23: Einstein's Bedload Model



3.8 Critical Stream Power

The movement of bed particles (or water) requires expenditure of energy, which is provided in streams by the release of potential energy as water travels down a slope. The rate of energy dissipation is a measure of the stream power of a reach and specifically describes the amount (per unit volume) of power made available by the decrease in potential energy of flowing water (Jonker, 2002) to maintain motion. This motion can be purely that of the fluid, or it can be of a fluid/solid mixture (Armitage & McGahey, 2003). A number of researchers have preferred to use unit stream power as an indicator of sediment motion, although this application is not generally described in standard hydraulic introductory texts.

Armitage & McGahey (2003) argue that the quantity represented by unit stream power is more directly related to entrainment threshold, because it can be computed at any point in the water column, and because turbulence is directly related to dissipation of energy. Rooseboom (1998) argues that the application of the law of conservation of stream power (over that for example of momentum which is the basis for equations of critical shear stress) has distinct advantages:

- It involves scalar quantities (unlike the momentum-impulse law).
- Its terms are directly time-dependent and account for the roughness of the bed directly.
- The stream power equations give theoretical and numerical support to the empirically derived components of the Liu Diagram for incipient motion (Liu, 1957).

3.9 Conclusion to Literature Review

As can be seen from the above literature review, there has been much work on developing an understanding of the parameters that define the threshold of movement for bed particles. In most cases this work has tended to focus either on laboratory experiments or small-grained sediments in natural rivers. It was found that there was little work that had been done on developing a hydraulic model to describe incipient motion in cobble and boulder bedded rivers.

It was also felt that the models developed under previous studies could not simply be adapted as those developed in laboratory flumes did not account for the complexities of turbulent flows in natural rivers, which becomes more critical in determining the incipient motion of large particles, while the models developed for fine-grained sediments could not be easily scaled up as the factors influencing incipient motion are not necessarily consistent across all scales.

In order to meet the objectives of this Project it would therefore be necessary to develop a new model, or at least adapt a suitably promising existing model to describe the onset of incipient motion in the two rivers being observed. Of the incipient motion models discussed above it was felt that the a model based on critical stream power was the most promising as it has a number of distinct advantages of the other models such as the Shields theory which is based on critical shear stress.

Some of the specific advantages of the power approach include the fact that stream power is:

- based on scalar quantification,
- takes into account the absolute roughness of the bed, and
- can be used to understand the parameters of the Liu diagram

The application of power theory to describe incipient motion in cobble and boulder bed rivers will be discussed in the following section of this Report. Having developed a new model to describe incipient motion in cobble and boulder bed rivers, this model was tested against the Shields model of critical shear stress. The results of this test are discussed in **Section 4.9**.

4. HYDRAULIC MODEL FOR INCIPIENT MOTION

4.1 Introduction

In order to meet the objectives of this study, two hydraulic models for incipient motion were developed. The first model was concerned with the threshold of movement for individual stones. This was developed in order to gain a better understanding of the forces experienced by a particular stone during a flood event so that these could be related to the level of disturbance in the invertebrate and periphyton communities in a subsequent phase of the project. It was decided that this model would be based on the movability number in the Liu Diagram, as this is a dimensionless term that is often used to describe incipient motion and the Liu Diagram is familiar to many people interested in stream hydraulics. Furthermore, it was decided to develop the model using the theory of the conservation of stream power.

The second model was developed in order to investigate the relationship, if any, between the DRIFT flood classification system and the level of bed disturbance. This would be useful in determining the impact that the reduction in the number of a certain class of flood under a managed flood regime would have on the disturbance of the bed particles and hence on the sustainability of the benthic communities. This model would therefore speak directly to the current system for determining environmental flow requirements. A simple empirical model was selected for this purpose and this was calibrated with the data collected during the thirteen flood events experienced at the two study sites.

4.2 Theory of Unit Stream Power

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

$$\int_{y_0}^{D} \rho gsv dy = \int_{y_0}^{D} \tau \frac{dv}{dy} dy \qquad (4.1)$$

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 velocity is mathematically equal to zero (m)

τ : shear stress at distance y above the bed (N/m2)

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

The parameter, ρgsv, represents the amount of unit power per unit volume 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 moveable material would only transport the material, if it results in a decrease in the amount of unit power being applied (Rooseboom, 1974; 1998).

The mechanism by which motion is maintained along the bed is different under laminar and turbulent conditions. Under laminar conditions energy dissipation occurs at the molecular level to overcome the forces between molecules. The amount of energy required to maintain motion is thus dependent on the viscosity of the fluid.

Under turbulent conditions energy dissipation occurs through the formation of turbulent eddies. The amount of energy required is thus dependent on the size of the turbulent eddies that form which is representative of the absolute roughness of the bed. As the power applied along the bed of a river varies depending on whether energy dissipation occurs under laminar or turbulent conditions, the critical condition for sediment movement also depends on whether energy dissipation occurs under laminar or turbulent conditions.

4.3 Incipient Motion Under Laminar Flow

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

$$\frac{(\rho gsD)^2}{\rho \nu} \tag{4.2}$$

In this equation the kinematic viscosity, ν , is significant as under laminar flow conditions, energy dissipation occurs at the molecular level.

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

$$(\rho_s - \rho) g V_{ss} \tag{4.3}$$

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

$$(V_{ss})_{LAM} \;\; \alpha \;\; d^2 g \frac{\rho - \rho_s}{\rho \nu} \tag{4.4}$$

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, a relationship defining the threshold for sediment transport under viscous conditions can be defined from the above equations. Rooseboom (1974,1998) calibrated this relationship with data by Grass (1970) and Yang (1973) and found that it could be defined by the following equation for smooth turbulent or laminar flow:

$$\frac{\sqrt{gDs}}{V_{ss}} = \frac{1.6}{\frac{\sqrt{gDs}}{\nu} \cdot d} \quad \textit{for} \;\; \sqrt{gDs}.d / \upsilon < 13 \tag{4.5}$$

4.4 Incipient Motion in Turbulent Flow

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

$$\tau \frac{dv}{dy} \approx \frac{30\rho gsD\sqrt{2\pi gsD}}{k} \tag{4.6}$$

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

$$(V_{ss})_{TURB} = \sqrt{\frac{4(\rho_s - \rho)gd}{3\rho C_d}} \tag{4.7}$$

In terms of the concept of minimum applied power, the stream will begin to entrain particles when the power required to suspend the particles becomes less than the power to maintain the status quo. At that stage:

$$(\rho_s - \rho)gV_{ss} \propto \frac{\rho gsD\sqrt{gDs}}{k} \tag{4.8}$$

where $(\rho_s - \rho)gV_{ss}$ represents the unit applied power required to lift a particle.

The left hand side of equation [4] can be expanded as follows:

$$(\rho_s - \rho)gV_{ss} = \frac{\rho C_D \cdot d(\rho_s - \rho)gV_{ss}}{\rho C_D \cdot d} = \frac{(\rho_s - \rho)gd}{\rho C_d} . \frac{\rho C_d V_{ss}}{d} \tag{4.9}$$

From **Equation 4.7** it follows that:

$$\frac{3}{4}V_{ss}^2 = \frac{(\rho_s - \rho)gd}{\rho C_d} \tag{4.10}$$

This can be substituted into **Equation 4.9** to give:

$$(\rho_s - \rho)gV_{ss} = \frac{3}{4}V_{ss}{}^2 . \frac{\rho C_d V_{ss}}{d} = \frac{3}{4}\frac{\rho C_d V_{ss}^3}{d} \tag{4.11}$$

Which, when substituted into the left-hand side of **Equation 4.8**, and replacing the proportionality relationship with a constant term on the right-hand side, leads to:

$$\frac{\rho C_D V_{ss}^3}{d} = \text{Constant} \cdot \frac{\rho gsD\sqrt{gDs}}{k} \tag{4.12}$$

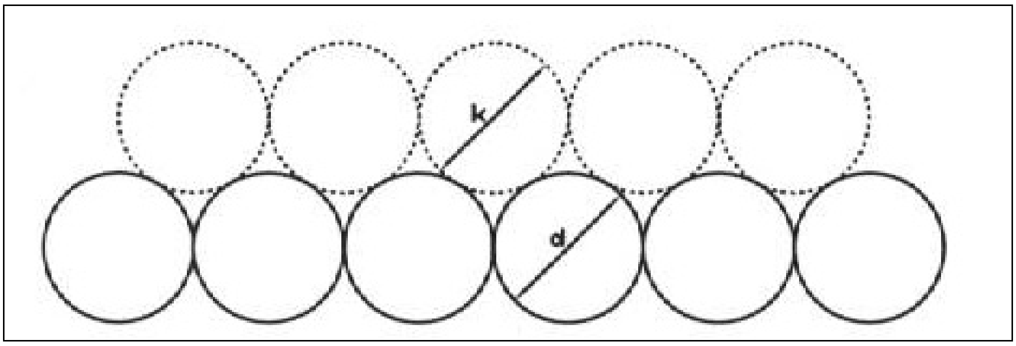
Assuming that C_D, the drag coefficient, is a constant, which is true for larger Reynolds numbers, then the above equation can be simplified to describe the condition of incipient motion under rough turbulent conditions for a non-uniform bed as:

$$\frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} = \text{Constant} \qquad (4.13)$$

4.5 Incipient Motion for Uniform Beds

Under turbulent conditions energy dissipation occurs through the formation of turbulent eddies. The size of these eddies represents the absolute roughness (*k*) of the bed. The development of eddies, on any bed, is a three-dimensional process. The bed configuration (in all directions) in the vicinity of a stone in the bed will determine the local eddy size. In the case of a bed with uniform size particles the eddy size would be of the same order as the particle diameter. This is shown in **Figure 24**.

Figure 24: Eddy Formation in a Uniform Particle Size Bed



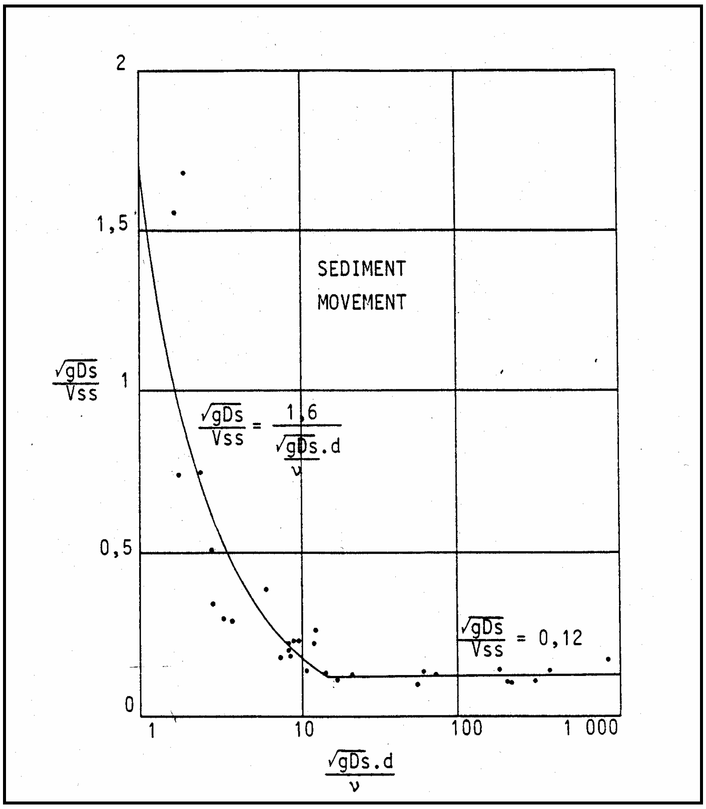
By substituting *k* with *d* in **Equation 4.13**, Rooseboom (1974) showed that the critical condition for the movement of sediment along an even uniform bed in rough turbulent flow can thus be defined by:

$$\frac{\sqrt{gDs}}{V_{ss}} = \text{Constant} \qquad (4.14)$$

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 $\sqrt{gDs}.d / \upsilon > 13$ (Rooseboom, 1974; 1998).

These results are plotted in the Liu Diagram (Liu, 1957) for incipient motion in **Figure 25** (Rooseboom, 1992). This diagram was originally developed on an empirical basis and fitting these equations to this plot enables us to understand the significance of the parameters involved and to provide the mathematical relationship, which describes critical conditions for incipient motion (Rooseboom, 2000).

Figure 25: Critical Conditions for Incipient Motion of Cohesionless Sediment



In terms of describing the parameters of the Liu Diagram, Rooseboom and Le Grange (2000) showed that the y-axis parameter $(\sqrt{gDs}/V_{ss})$, which is called the Movability Number, represents the ratio:

$$\frac{\text{Unit power applied along bed}}{\text{Unit power required to suspend particles}}$$

Similarly the x-axis parameter, $(\sqrt{gDs} \cdot d/\nu)$, which is known as the Particle Reynolds number (Re_*) represents the ratio:

$$\frac{\text{Unit applied laminar power}}{\text{Unit applied turbulent power}}$$

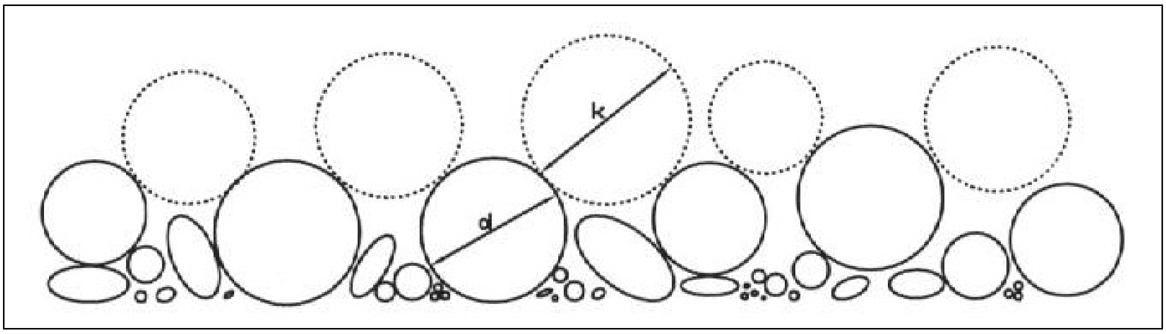
A plot above the threshold line in **Figure 25** therefore implies that the unit power applied along the bed is greater than the unit power required to suspend particles.

Critical conditions for the movement of sediment along an even bed in rough turbulent flow are thus defined by a straight horizontal line with a constant value of $(\sqrt{gDs}/V_{ss}) = 0.12$. In laminar or smooth turbulent flow incipient motion becomes dependent on viscosity and the relationship defining the threshold for sediment transport is defined as $\sqrt{gDs}/V_{ss} = 1.6/(\sqrt{gDs} \cdot d)/\nu$.

4.6 Incipient Motion for Non-uniform Beds

In the case of a non-uniform particle size bed, the relationship between the size of the turbulent eddies that form and the particle size is not as straight forward as for a uniform bed. **Figure 26** depicts a two-dimensional representation of the eddy formation process in a non-uniform particle size bed.

Figure 26: Eddy Formation in a Non-uniform Particle Size Bed



Because flow resistance across the bed is developed over distance it may be assumed that the average eddy size across a non-uniform bed will tend towards uniformity, with the average eddy size of the same order as that of the larger stones. As a result the absolute roughness (*k*), which is linked to the size of the eddies that form above the bed, will also be of the same order as that of the large stones and this will tend towards uniformity across the bed.

On a bed of non-uniform bed particles, the absolute roughness (*k*) is therefore not equal to individual particle diameter (*d*) as it is on a bed of uniform size distribution. Hence equation [8] cannot be reduced to $\sqrt{gDs}\,/\,V_{ss}$ when applied to a bed of non-uniform particle size distribution, but must retain the additional $(d/k)^{1/3}$ term. This therefore represents a new definition of the Movability Number for beds of non-uniform size distribution.

4.7 Incipient Motion in Cobble and Boulder Bed Rivers

The objective in developing a theoretical mathematical model to describe incipient motion of bed particles was to be able to use the model to predict the likely movement, or non-movement of individual stones under a particular flood event in cobble and boulder bed rivers. This could then be used in conjunction with the observed ecological disturbance levels to develop guidelines on the size of flood required to generate a certain level of bed disturbance in order to maintain a healthy aquatic ecosystem.

The mathematical model developed above shows that the point of incipient motion for an individual bed particle on a bed of non-uniform particle size distribution is dependent on the ratio of the unit stream power applied to the bed under a particular flood event and the unit stream power required to move the particle.

This relationship was shown to be represented by the following equation:

$$\frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} = \text{Constant} \qquad (4.15)$$

As a first approximation for the absolute roughness (*k*) in the above equation, it can be assumed that the average size of the turbulent eddies is relative to the average size of the larger particles which define the absolute roughness. In this case, the size of the particle representing the 84th percentile (d_{84}) was used. This represents one standard deviation above the mean and was informed by work done by Charlton *et al.* (1978) and Jonker *et al*. (2002) who both found d_{84} to be representative of the average bed roughness under conditions of large scale roughness. To account for the fact that the depth of water above certain particles during some of the flood events was less than d_{84}, the average eddy size (*k*) above individual stones was taken as the minimum of the maximum flow depth (*D*) and d_{84}.

The impact of the additional (*d/k*) term can be seen by comparing **Figure 27**, which plots the data from the observed flood events in the Berg using the normal usual Movability Number ($\sqrt{gDs}/V_{ss}$), and **Figure 28**, which plots the same data using the revised Movability Number taking account of the non-uniform bed material $((\sqrt{gDs}/V_{ss}).((d/k)^{1/3})$.

The results from the five flood events observed at the Berg River site in 2004 are plotted below to show the relationship between the moved and non-moved stones in the Liu diagram with the modified Movability Number, to account for the non-uniformity of the bed particles. The only difference between **Figure 28** and **Figure 29** is the scale of the y-axis.

The observed data in the Molenaars River for 2003 and 2004 are plotted in the **Figures 30 and 31**, also using the modified Movability Number to represent the ratio of applied power to required power on a non-uniform bed.

Figure 27: Berg River Data Plotted in Liu Diagram using Original Movability Number

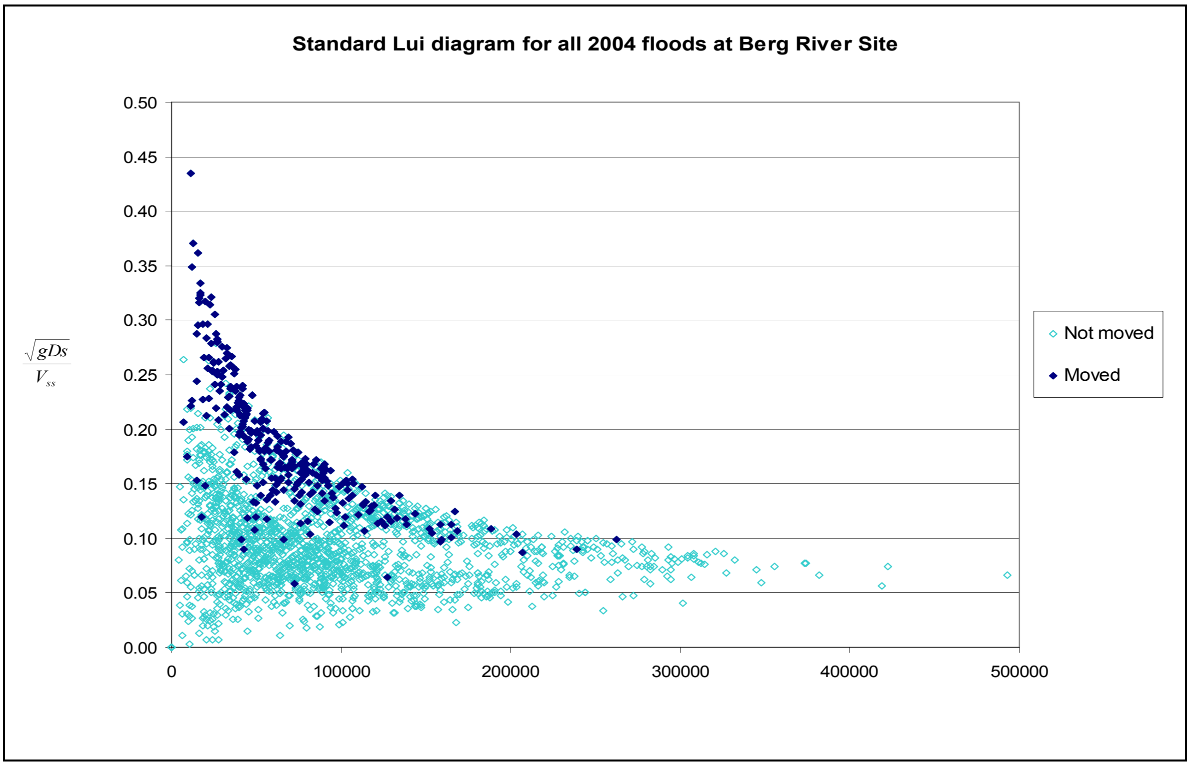


Figure 28: Berg River Data Plotted in Liu Diagram using Modified Movability Number

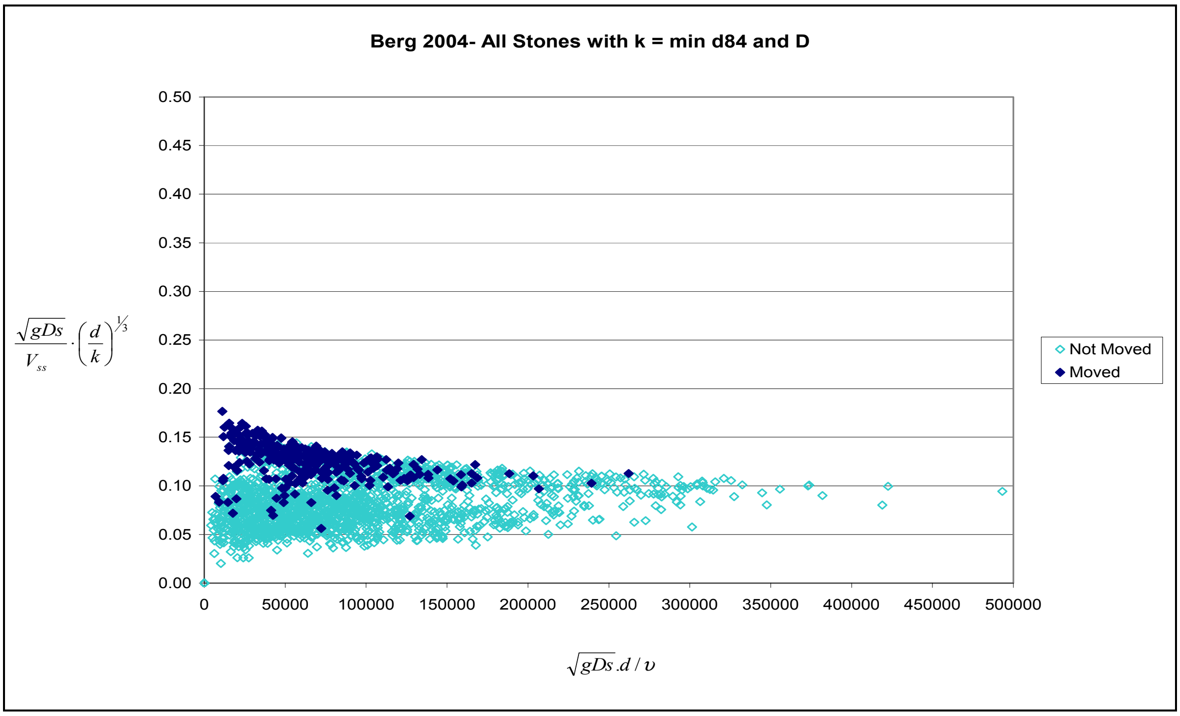


Figure 29: Observed Movement of Stones at the Berg River Site: 2004 Floods

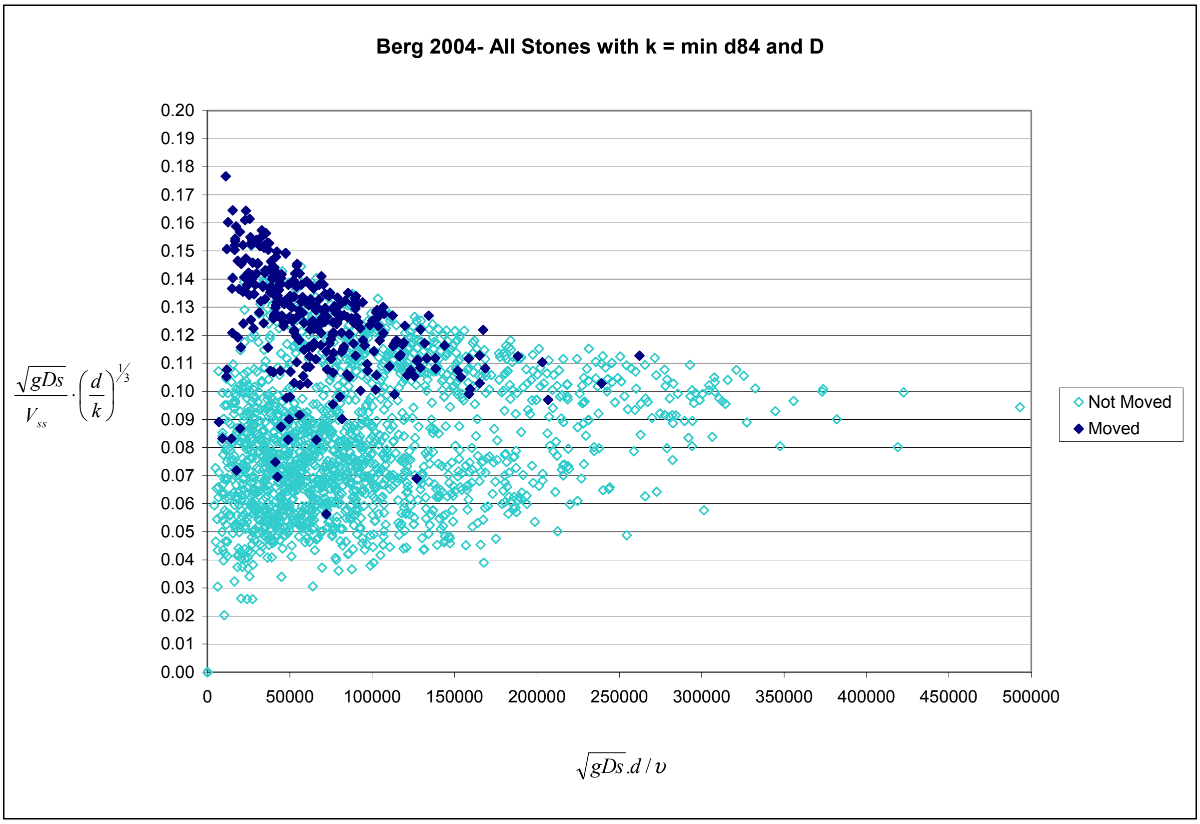
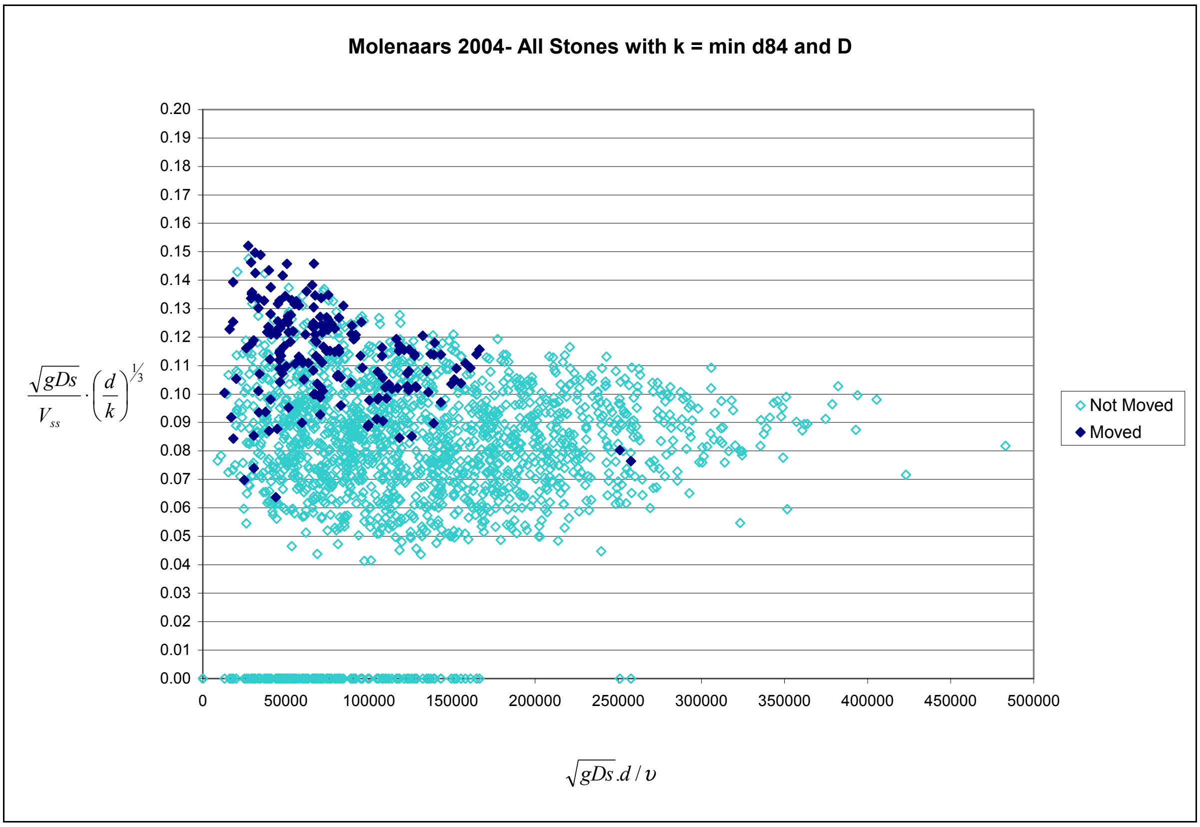


Figure 30: Observed Movement of Stones at the Molenaars River Site: 2003 Floods

Figure 31: Observed Movement of Stones at the Molenaars River Site: 2004 Floods



The unit stream power model predicts that the point of incipient motion, i.e. the boundary between movement and non-movement, should be described by a constant value of the Movability Number which represents that ratio of applied power to required power, i.e. **Equation 4.15**.

As is to be expected given the high variability of flow in cobble and boulder bed rivers, there is likely to be some degree of scatter about this constant threshold of movement both in terms of stones that moved at a lower ratio of applied power to required power and stones that remained unmoved at a relatively high value of applied power. This is seen in the above plots which do not show a clear distinction between moved and non-moved stones, but clearly show an increase in the number of moved stones with an increase in the Movability Number.

This scatter in the threshold of movement can be attributed to a number of factors including:

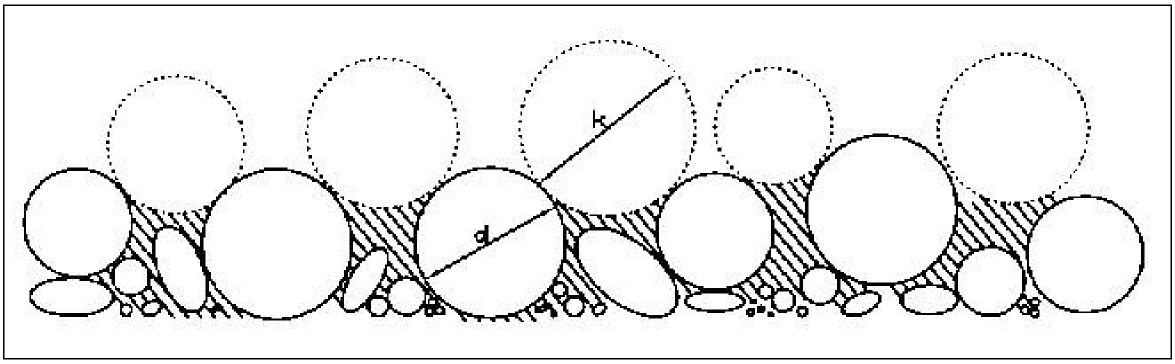
1. variation in the eddy size across the bed (changes k)
2. fluctuations in the eddy size due to pulses in the turbulent flow regime (changes k)
3. movement may occur well before the maximum flood level is recorded (changes k, D and s)
4. duration of flood event and hence the time for which a particle is exposed to a particular level of applied power.
5. localised variations in the water and energy slope (changes D and s)
6. variations in the shape of the bed particles (changes V_{ss})
7. possible pinning down of the bed particles by other particles (changes V_{ss})
8. movement of particles induced by other saltating particles (increases applied power)
9. degree of embeddedness (changes V_{ss})
10. observation errors

Some of these factors could be accounted for through further research and more detailed observations of the movement of stones under laboratory and field conditions, particularly in terms of defining the absolute roughness (k) and the local energy slope (s) for individual stones. Ultimately, however, there will always remain a certain degree of uncertainty with regards to the movement of bed particles. It is therefore important that incipient motion be considered not as a clearly defined point, but as a range of increasing probabilities for the movement of an individual stone. This will be addressed in the following section, but firstly it is important to consider the impact of embeddedness and overlapping cobbles.

In environmental hydraulics, embeddedness refers to finer particles and sediments such as sand that fill the spaces between cobbles on the bed. In terms of the incipient motion of the cobble, unless the finer sediments are cohesive, the embedding of a cobble in this way will not affect the critical conditions for movement in terms of applied power. This is because the point of incipient motion for the cobble is at a much higher level of applied power than for the finer sediment due to the much greater settling velocity. Hence, by the point of incipient motion of the larger cobble, the finer sediment would already have been scoured from between the cobbles.

This, however, assumes that turbulent flow occurs between the cobbles and that the applied power generated by the main turbulent structure is translated to flow transition zones that form between the cobbles and below the main turbulent structure of the river as shown in **Figure 32**.

Figure 32: Transition Zones Formed Below the Main Turbulent Structure of the River



The model developed in this Study did not look at the flow structure in these transition or sheltered zones, relying instead on consideration of only the main turbulent structure of the river as defined by the average bed roughness. The impact of a different flow structure in these areas may result in some of the scatter in the data points and may also affect the potential influence of embeddedness on the incipient motion of cobbles and boulders.

In an extreme case, laminar flow may occur in the sheltered spaces between the cobbles. Rooseboom and le Grange (2000) showed this to be the case for the formation of dunes under flood events in sand-bedded rivers. The settling velocity of a particle is much greater under laminar flow conditions than under turbulent conditions and could result in fine sediment located between the cobbles requiring greater applied power to initiate movement than the larger cobble, which is subject to a turbulent settling velocity. It is therefore important that further work be done to investigate flow under flood conditions in these transition zones, the impact that this will have on embeddedness and incipient motion, and the local bed roughness.

A second issue that needs to be considered is the possibility that a cobble is pinned by another, larger cobble. In the case of a natural river, the arrangement of particles on the bed is not random as it would be in a laboratory, but has been sorted by the passage of numerous floods and low flow events. As a result there is a certain degree of order on the bed. This natural ordering of the bed requires further study in cobble and boulder bed rivers, but the implication for incipient motion is that when considering the movement of stones on an average reach basis the impact of pinning down of cobbles by other cobbles will balance out if different rivers or different parts of a single river can be considered to be scale models of each other. The results of this study (particularly **Figure 36**) show this to be the case when comparing the Molenaars and Berg River.

4.8 The Probability of Movement of Individual Stones

As a first attempt to describe incipient motion in terms of the increasing probability of movement of an individual stone, rather than as a unique value, the degree of movement within particular constant bands for the Movability Number, or ratio of applied power to required power, was investigated. The number of moved and non-moved stones in each band for the five observed floods at the Berg River site are given in **Figure 33**, where the Movability Number given on the x-axis represents the value at the mid-point of each band.

The number of moved and non-moved stones in each band for the six observed floods in 2003 at the Molenaars River site are given in **Figure 34**, and for the five observed floods in 2004 in **Figure 35**.

A summary of the results in terms of the percentage of movement in each band for the three sets of flood data, Molenaars 2003, Molenaars 2004, and Berg 2004 are plotted in **Figure 36**.

Figure 33: Movement of Stones Grouped by Movability Number: Berg 2004

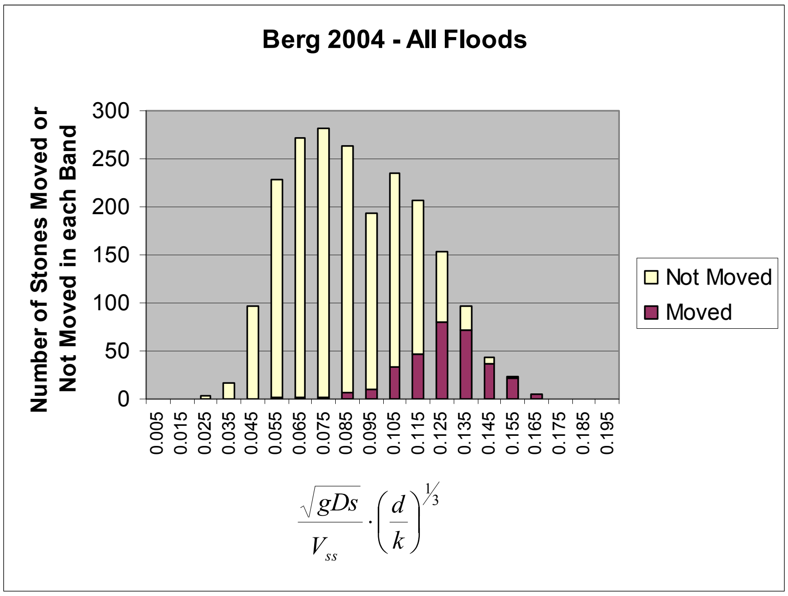


Figure 34: Movement of Stones Grouped by Movability Number: Molenaars 2003

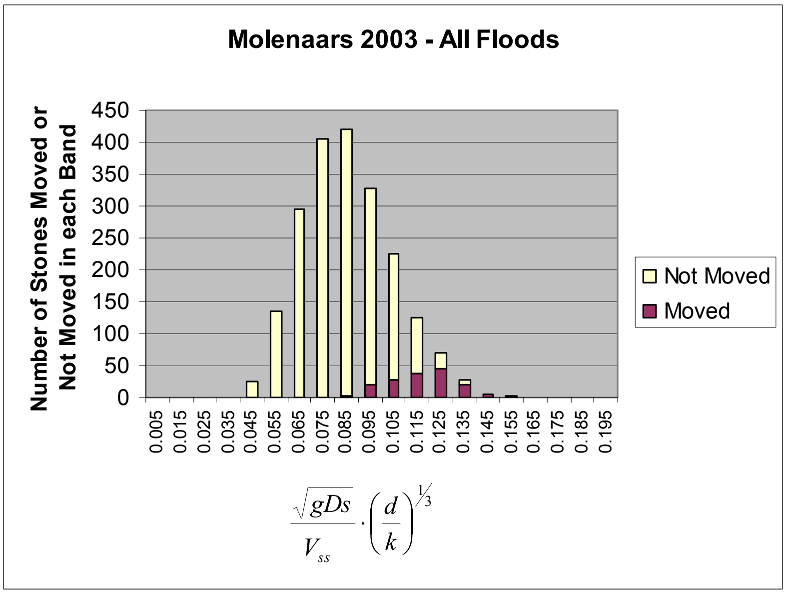


Figure 35: Movement of Stones Grouped by Movability Number: Molenaars 2004

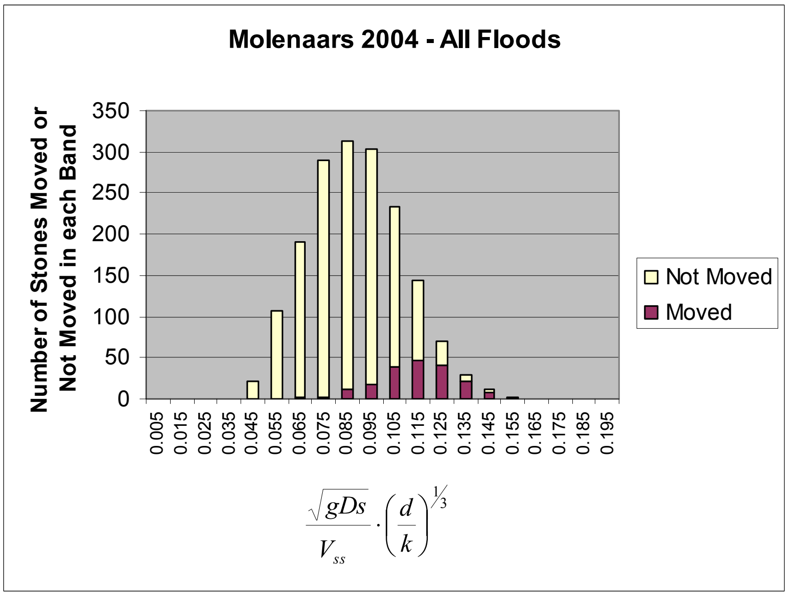
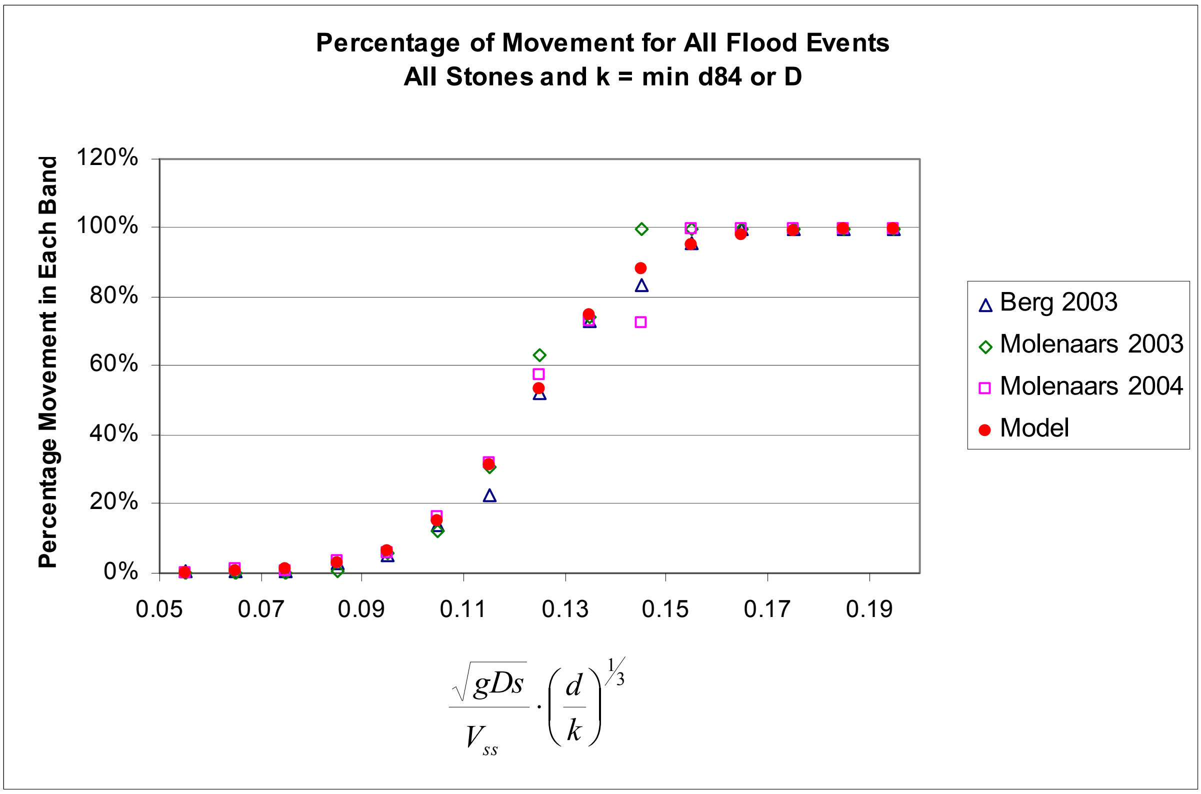


Figure 36: Percentage of Movement of Stones in Relation to Movability Number: All Stones for All Flood Events



The results from all three sets of flood events appear to describe the same relationship between the percentage of movement and the ratio of applied power to required power. This relationship can be modelled by a simple logistic curve of the form:

$$PM = \frac{A.B.e^{r.C}}{A - B + B.e^{r.c}} \quad \text{with} \quad M = \frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} \qquad (4.16)$$

where *PM* :The expected percentage of movement
A : The maximum percentage of movement (99.999%)
B : The minimum percentage of movement (taken as 0.001%)
M : The Movability Number
r : The rate of increase in the percentage of movement

By minimising the sum of the squares of the differences for all the results, it was found that the best fit was obtained when r = 93.26. The modelled results using this relationship are also shown in **Figure 36**. The results for the T-test for the three sets of data and the modelled results are given in **Table 9** and show a very strong correlation.

Table 9: T-Test Results for all Three Sets of Flood Data and the Model Predictions

	Berg03	Mol03	Mol04	Model
Berg03	1.000			
Mol03	0.901	1.000		
Mol04	0.968	0.932	1.000	
Model	**0.959**	**0.940**	**0.991**	**1.000**

If the definition for incipient motion is interpreted as the point at which a stone is more likely to move than to not move, i.e. the probability of movement is greater than 50%, and the probability of movement of an individual stone is equal to the percentage of movement observed for the given Movability Number, then the model developed above can be used to determine the critical Movability Number or ratio of applied power to required power at this point.

The critical Movability Number (i.e. the *MN* term in **Equation 4.16** that resulted in an estimated 50% movement) was found to be equal to 0.123. The conclusion is that incipient motion in cobble and boulder bed rivers of non-uniform particle size distribution, i.e. the point at which a particular stone is more likely to move than to not move, can be defined by the following relationship:

$$\frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} = 0.12 \qquad (4.17)$$

with D : flow depth, measured to the top of the stone.
d : individual stone diameter measured on the second longest axis
s : energy slope (can use water slope, or even average bed slope)
V_{ss} : Turbulent settling velocity ($V_{ss} = \sqrt{\frac{(\rho_s - \rho)gd}{\rho C_d}}$)
k : absolute bed roughness (k = minimum of d_{84} or D)
d_{84} : particle diameter for which 84% of particles are smaller
C_d : drag coefficient ($C_d = 0.4$)
ρ : density of water
ρ_s : density of particle
g : acceleration due to gravity (g = 9.81)

This result is consistent with the definition of incipient motion for turbulent flow on a bed of uniform particle size distribution as determined by Rooseboom (2000):

$$\frac{\sqrt{gDs}}{V_{ss}} = 0.12 \qquad (4.18)$$

The difference between the two definitions of incipient motion is that the latter one does not include the term that accounts for the difference between the individual particle size (*d*) and the absolute roughness of the bed (*k*), as for beds of uniform particle size distribution the absolute roughness can be considered to be equal to the particle size ($k \approx d$).

It is important to note that this relationship was developed using data obtained from only thirteen flood events and from only two streams. The average bed slope of the Molenaars study reach was 0.018 m/m and for the Berg studies reach it was 0.015 m/m. The observed particles were all in the cobble to boulder range with a maximum stone size of just over 1m in diameter. The d_{84} for the Molenaars study reach was 538 mm while the d_{84} for the Berg study reach was 372 mm. The d_{50} for the Molenaars study reach was 248 mm while the d_{50} for the Berg study reach was 205 mm.

It is unclear at this stage if **Equation 4.17** represents a universal finding for all rivers of non-uniform particle size distribution. To be able to answer this will require the model to be tested on other rivers. The results from the two rivers tested, however, were consistent despite being of different size and having different stone size distribution. Based on this observation it could be hypothesized that the above results will be universal at least in the case of cobble and boulder bed rivers.

4.9 Predicting the Movement of Individual Stones

To check the above model for determining the movement of stones, it was used to predict the likely movement of stones under the observed flood event conditions and then compared to the actual observed stone movement. In terms of predicting the movement of stones using the applied power model, two scenarios were tested. The first used the observed average water slope for an approximation of the energy slope (*s*) and the second scenario simply used the average bed slope of the study reach. In addition to testing the predicted movement using the applied power model, three scenarios for the shear stress model were used. The equation for the shear stress model used is based on that of Komar (1987). This equation was developed to account for a naturally mixed-particle size bed.

$$\tau_{crit} = \theta_{crit}(\rho_s - \rho)g.d_{50}^{0.6}.d^{0.4} \qquad (4.19)$$

Komar (1987) used a value for θ_{crit} of 0.045 based on the work of Miller *et al*. (1977). Andrews (1983), however, suggested that θ_{crit} approached a minimum value of 0.02 and it was concluded by Lorang and Hauer (2003) that this was the best estimate for natural rivers with higher gradient channels. The two values for θ_{crit} were used as two scenarios for the testing of the shear stress model.

A third shear stress scenario used a value for θ_{crit} that was calibrated using the observed data. This value of θ_{crit} was selected so as to correctly predict the total number of stones that moved.

A number of indicators were used to determine the ability of the above model scenarios to predict the movement of individual stones. These are given in **Table 10**.

Table 10: Indicators used to Compare Models of Incipient Motion

Indicator	Description
Correct – All	Predicted to move and did move, or predicted to not move and did not move as a percentage of all stones
Correct – Moved	Predicted to move and did move as a percentage of all the stones that did move
Correct – Not Moved	Predicted to not move and did not move as a percentage of all the stones that did not move

Of these three indicators the first one, i.e. the ability to correctly predict both the movement and non-movement of stones is the most significant. From a hydraulic point of view this is important, as it gets closer to defining the threshold of movement. If the model results in a threshold of movement that is too low, this results in an over prediction of stone movement. This gives one a very good result in terms of the "correct-moved" indicator, but a poor result on the "correct – not moved" and the "correct – all". This is appropriate if the intention is to ensure that you get at least a given level of bed disturbance, and you are not worried about getting too much bed disturbance.

For setting of flood levels for environmental water requirements, however, it is important to get a balance between moved and non-moved stones. While you want to ensure that you get a certain minimum amount of bed disturbance, you do not want to prescribe a flood that is too large which may result in too much bed disturbance. This is important from an ecological perspective as too much disturbance can be as bad, if not worse than too little disturbance, but is also important when the water being released has an economic value, i.e. is released from a reservoir where it could otherwise have been sold to consumers. For this reason it is important that the model can be used to identify as accurately as possible the threshold between moved and non-moved stones. This is achieved by striving to maximize the "correct- all" indicator.

The results of the ability of the various model scenarios to predict the movement of the individual non-embedded stones for the three sets of observed data are given in the following tables. This shows the number of stones predicted to move using each model and compares this to the number of stones that were observed to have moved. The ability to predict the movement of stones is indicated in the three right-hand columns, which relate to the indicators described above.

Table 11: Predicting the Movement of Individual Stones: Molenaars 2003

Predicted Movement	Factor	Moved (count)	Moved (%)	Correct All	Correct Moved	Correct Not Moved
Applied Power (Sw)	0.120	57	6.88%	93.24%	50.57%	87.92%
Applied Power (So)	0.120	75	9.06%	93.24%	60.92%	86.84%
Shear Stress (Komer)	0.045	354	42.75%	67.27%	97.70%	57.00%
Shear Stress (Alexandre)	0.020	776	93.72%	16.79%	100.00 %	6.28%
Shear Stress (Maximised)	0.080	57	6.88%	93.00%	49.43%	87.80%
Observed Movement		87	10.51%			

Table 12: Predicting the Movement of Individual Stones: Molenaars 2004

Predicted Movement	Factor	Moved (count)	Moved (%)	Correct All	Correct Moved	Correct Not Moved
Applied Power (Sw)	0.120	107	11.04%	84.93%	39.23%	95.43%
Applied Power (So)	0.120	170	17.54%	85.04%	56.91%	91.50%
Shear Stress (Komer, 1987)	0.045	530	54.70%	61.71%	93.92%	54.31%
Shear Stress (Andrews, 1983)	0.020	936	96.59%	22.08%	100.00 %	4.19%
Shear Stress (Calibrated)	0.080	110	11.35%	85.86%	42.54%	95.81%
Observed Movement		181	18.68%			

Table 13: Predicting the Movement of Individual Stones: Berg 2004

Predicted Movement	Factor	Moved (count)	Moved (%)	Correct All	Correct Moved	Correct Not Moved
Applied Power (Sw)	0.120	295	18.97%	88.55%	69.31%	75.05%
Applied Power (So)	0.120	562	36.14%	79.61%	90.43%	61.99%
Shear Stress (Komer, 1987)	0.045	722	46.43%	71.64%	96.37%	52.86%
Shear Stress (Andrews, 1983)	0.020	1283	82.51%	36.85%	99.67%	17.43%
Shear Stress (Calibrated)	0.090	244	15.69%	89.00%	62.05%	76.91%
Observed Movement		303	19.49%			

From the above results it is clear that the applied power model gives good results in terms of predicting the movement of individual stones as well as the total percentage of movement. The ability to predict whether a stone will move or will not move under a particular flood event (i.e. the "correct-all" indicator) is above 85% when using the average water slope and above 80% when using the average bed slope. In terms of the shear stress model, it is clear that values for θ_{crit} of 0.045 (Komer, 1987) and 0.02 (Andrews, 1983) both overpredict the number of stones that will move. If, however, the calibrated value of θ_{crit} (0.08) is used then the ability to predict the movement or non-movement of stones using the Shear Stress model is similar to that of the applied power model.

4.10 Stream Competence Related to Drift Flood Class

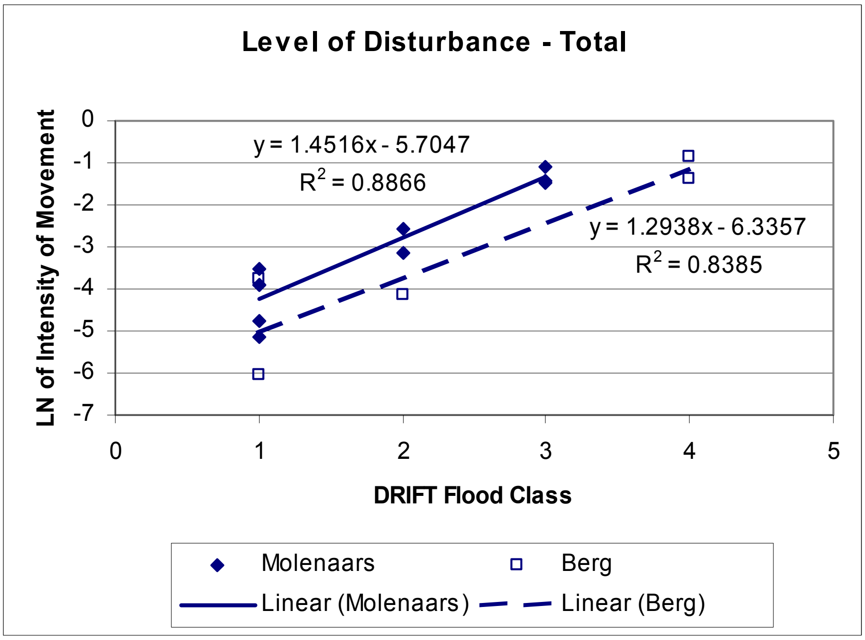
Under the DRIFT methodology, experts have to decide on the impact of reducing or increasing the number of various flood classes in a managed flow regime. The DRIFT classification system is explained briefly in **Section 2.4**. The intra-annual floods levels were developed in response to a need for an aquatic scientist to have a system for describing flood events normally not considered in standard hydraulic descriptions of a river or from a statistical analysis of the annual flood maxima. The maximum flow rate for each of the intra-annual flood classes was derived by halving the two-year return period flood to obtain the Class 4 flood, which was halved again to obtain the Class 3 flood, and so on for the Class 2 and Class 1 intra-annual floods.

Little consideration has been given to what each of these flood classes represents, but this is vital to the DRIFT methodology in terms of understanding the importance of each of these flood classes. The objective of developing this model was to investigate the relationship between the level of disturbance of the bed particles and the flood class, which could assist in the assessment of the likely impact of reducing the number of floods of a certain class.

In developing this model it was assumed that there would be an increase in the level of disturbance related to an increasing flood class, as a result of the increase in the maximum flow rate. It was, however, hypothesised that this would not be a linear relationship due to the way in which the flood classes are selected. The classification of the flood events observed at the two study sites is shown in **Section 2.4**. This was based on a comparison of the observed average daily flows with those determined for each intra-annual flood class in previous studies.

The level of bed disturbance, hereafter referred to as the intensity of movement, was a simple reach average disturbance level calculated as the percentage of the observed stones that moved during a particular flood event. A plot of the natural log of the intensity of movement (*I*), with the DRIFT flood classification (*DC*) was found to best represent the relationship. This plot (**Figure 38**) shows a strong log-linear relationship with $R^2 = 0.89$ and $R^2 = 0.84$ for the Molenaars and Berg River data, respectively.

Figure 37: Plot of DRIFT Flood Classification and Intensity of Movement



This log linear relationship implies that:

$$Ln(I) = a.(DC) - b \quad \text{or} \quad I = \frac{e^{a.DC}}{c} \qquad (4.20)$$

where *I* : intensity of movement,
DC : DRIFT classification, and
a, b, c : constants for a given reach

The plots of the individual stone size fractions show a similar linear relationship and the constant terms and R^2 values for both sites are shown in **Table 14** and **Table 15**.

What is apparent from these two tables is the similarity between the coefficients for the small cobble, large cobble and small boulder fractions of the Molenaars study site. These are the fractions for which there is the most data, not only in terms of the number of floods in which disturbance was caused in these fractions (n), but also in the stone size distribution of the sampled stones (79% of the sampled stones on the Molenaars study reach fall into these three categories).

The coefficients for each of these particle size classes are also similar to the total level of disturbance in the Molenaars study reach, particularly if one considers the possible sources of error introduced by the relatively low number of data points for the gravel and large boulder components.

Table 14: Coefficients for each particle size: Molenaars River

Particle Class	a	b	c	R^2	N
Gravel	0.72	2.63	2.05	0.68	5
Small Cobble	1.35	5.37	3.87	0.81	8
Large Cobble	1.35	4.47	3.86	0.81	10
Small Boulder	1.34	6.13	3.80	0.94	5
Large Boulder	Insufficient data points				2
Total	1.45	5.71	4.27	0.89	10

Table 15: Coefficients for each particle size: Berg River

Particle Class	*a*	*b*	*c*	R^2	n
Gravel	0.86	4.11	2.37	0.80	5
Small Cobble	1.15	5.18	3.16	0.95	4
Large Cobble	0.96	4.92	2.60	0.84	4
Small Boulder	0.74	4.98	2.09	0.96	3
Large Boulder	Insufficient data points				2
Total	1.29	6.34	3.65	0.85	5

One can therefore hypothesize that the relationship between the DRIFT flood classes and the level of disturbance can be described for the Molenaars river as:

$$I = \frac{e^{1.35C}}{3.85} \tag{4.21}$$

In the Berg River, the descriptive variables (*a* and *c*) appear to be slightly lower. This may be due to either the flatter nature of the Berg River site (S_0 = 1.45% as opposed to S_0 = 1.79% for the Molenaars) or the slightly smaller stone size distribution (d_{50} = 205 mm as opposed to d_{50} = 240 mm for the Molenaars) or some other reach characteristic that distinguishes between them. It may also however simply be a reflection of the limited data on the Berg River with data only available from five flood events, only four of which were sufficiently large to cause disturbance in the cobble and boulder size range.

To test for the relevance of these other reach characteristics the average value for the *a* and *c* constants for the small cobble, large cobble and small boulder fractions were taken as the constants describing the intensity of movement in the terms of the DRIFT flood classification. Hence:

$$I = \frac{e^{0.95DC}}{2.62} \tag{4.22}$$

If an additional reach characteristic variable (α) to account for the difference in the slope and particle size distribution for the two sites is introduced, then the relationship between the intensity of movement (I) and the DRIFT flood classification (DC) can be described approximately by a single equation for both study sites as follows:

$$I = \frac{e^{34.3.\alpha.DC}}{96.9.\alpha} \quad \text{where} \quad \alpha = S_0 \frac{d_{84}}{d_{50}} \qquad (4.23)$$

It is important to note that this reach factor (α) is only provisional at this stage. The above relationship is based on a few samples in only two rivers in the Western Cape. The above equation is therefore a proposal for a possible form of universal relationship between the intensity of movement (I), the DRIFT flood class (DC) and the specific reach characteristics (α). Further research and testing of this relationship on other rivers is important before the above relationship can be considered for use in Reserve determination or other studies.

5. GUIDELINES FOR DETERMINING SUBSTRATE MAINTENANCE FLOWS

The general approach to determining substrate maintenance flows described in this Section is intended primarily to be used in the DRIFT model for environmental flow assessments. It can, however, just as easily be incorporated into any other environmental flow assessment technique that requires consideration for the link between flood magnitudes, stone movement and ecological disturbance associated with this stone movement.

It is important to note that the recommendations given in this Section arise from this study only. These are therefore preliminary recommendations only and need to be considered as part of the general discussions on the requirements for environmental flow assessment studies.

5.1 Requirements for DRIFT

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

1. Identification and isolation of wet-season and dry-season low flows, freshes, and floods from the long-term record,

2. Description of the consequences for the river of partial or whole removal of each of these flow components,

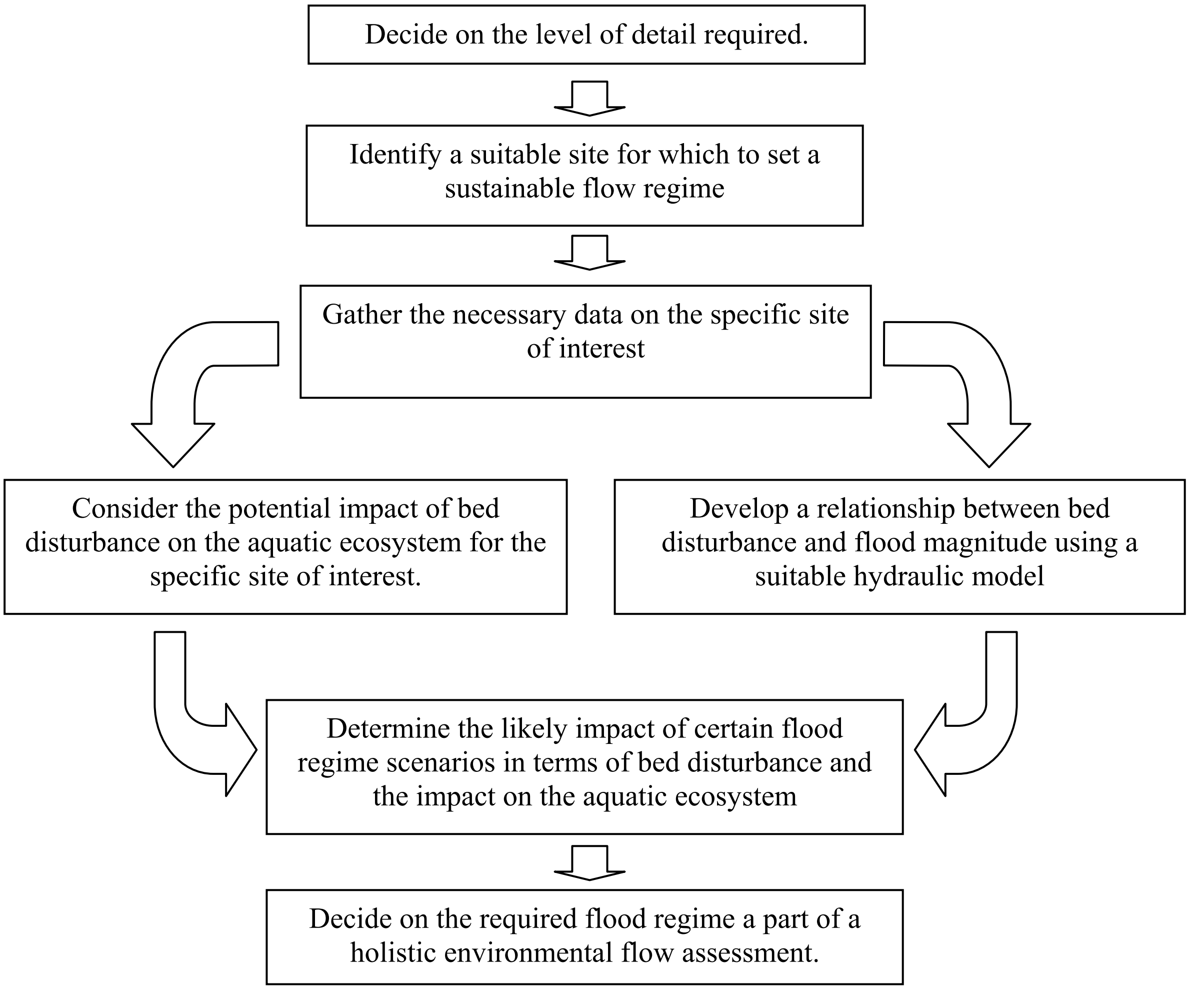
3. Creation of a bio-physical database detailing the consequences,

4. Use of the database to describe how river conditions will change with any future combination of high and low flows removed, and

5. Describe the socio-economic implications of changes in river condition.

The recommended general approach for determining substrate maintenance flow requirements that should be considered for incorporation into the environmental flow assessment methodology is depicted in **Figure 38**. A more detailed description of the guidelines for each step is given below.

Figure 38: General Approach to Determining Substrate Maintenance Flows



5.2 Decide on the Level of Detail Required

A comprehensive environmental flow assessment can be a very costly and time-consuming exercise, given the relatively limited amount of readily available information on environmental flow requirements and the degree to which these requirements are site specific. Given this concern it is important to consider upfront the level of detail required for determining the substrate maintenance flow requirements. This will be governed by the value of the resource being considered, the availability of resources as well as the relevance of substrate maintenance flows as part of the environmental flow assessment. The distinction is also made in terms of the level of Reserve being considered. If a Comprehensive Reserve determination is required, then the level of detail required will be much greater than that for an Intermediate Reserve determination study.

In terms of developing tools to address this need to consider the level of detail required, two hydraulic models have been developed that can be used to determine the substrate maintenance flow requirements. One is a simple empirical model that looks at the relationship between DRIFT flood class (*DC*) and the average level of bed disturbance due to a particular flood class (i.e. the percentage of stones that will be moved by a particular flood event) referred to as the intensity of movement (*I*).

This model is discussed in **Section 4.8**.

The second model is more detailed and looks at the potential movement of individual stones under a particular flood event based on a critical Movability Number, which represents the ratio of applied power to required power. This model is discussed in **Section 4.6**.

The advantage of the second model is that it enables a much more detailed understanding of the differential impact on organisms in the study reach, while it is only possible to make a rough estimated of the overall impact on aquatic organisms using the first method. The proposed application of these two models in determining substrate maintenance flow requirements is discussed in more detail in **Section 5.5**.

5.3 Selection of a suitable site

These guidelines refer specifically to substrate maintenance flows in cobble and boulder bed rivers and as such are only applicable in rivers of this nature. A more detailed description of the requirements for site selection and data collection for Reserve determination studies in general is given in the DWAF's Resource Directed Measures Manual.

The general location of the site for which a managed flow regime will be set will largely be determined by the reason for setting the flow regime in the first place. As it is more cost-effective to select as few sites as possible for determining environmental flow requirements, it is important that the requirements for a suitable site for determining substrate maintenance flows be considered when looking for a suitable site and *vice versa*.

To make the hydraulic calculations simpler it is suggested that a straight section of river be selected that is fairly uniform and where it can be anticipated that uniform flow will develop under flood conditions. The total length of the identified site should be approximately 50 m so that it is possible to get a fair representation of the average bed slope and it should be on a straight section of river with few or no major obstacles affecting the flow, i.e. it should be hydraulically simple. An example of a good site is that of the section of the Molenaars River used as part of this research project. Other factors such as accessibility, existing information, and the presence of a flow gauging station should also be considered.

5.4 Data to be collected for Specific Site of Interest

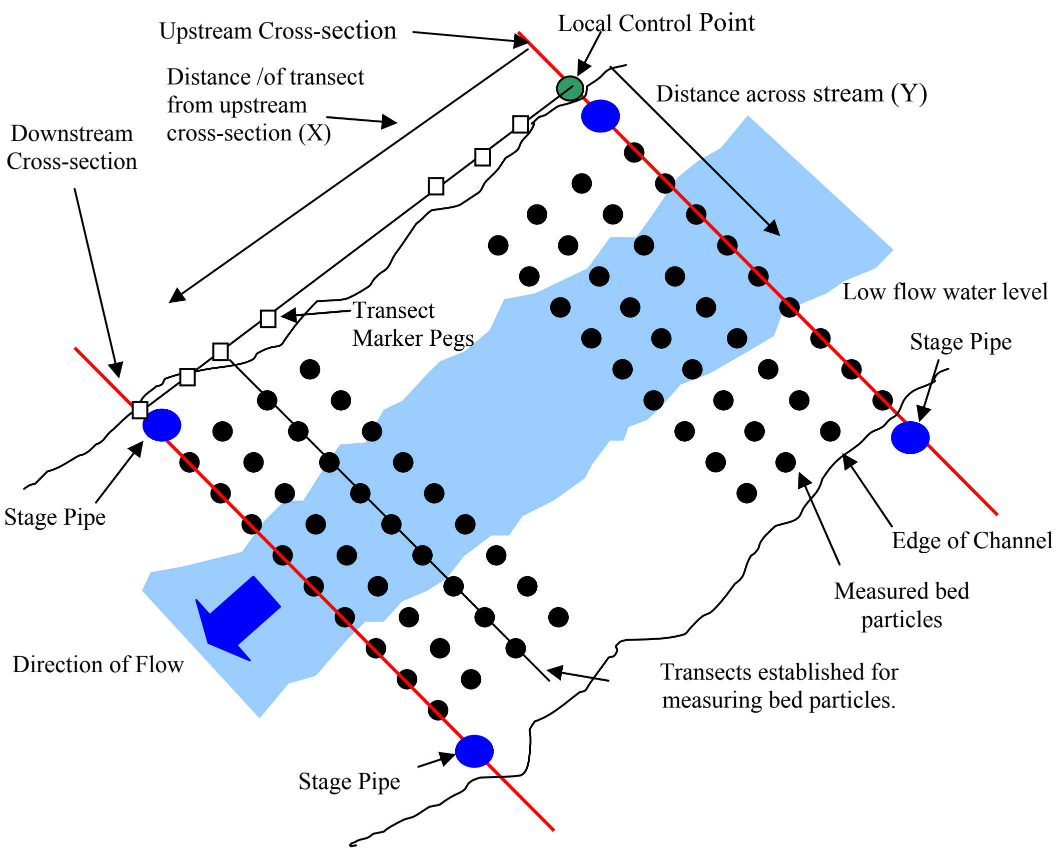
Having selected a suitable site it is important to gather the necessary data from the site. The most important hydraulic data for determining substrate maintenance flows is the size distribution of a representative sample of bed particles and the relevant elevation of the stones. Other important information is the average bed slope and the river cross-sections that will enable the development of a depth to discharge relationship.

The recommended approach for collecting this data is to first set-up a number of transects along the selected reach (say 25 transects at 2 m intervals). Stones are randomly selected along each transect based on the recommended method of sampling by Woolman (1955) by using a spacing along each transect of between 1 m and 2 m intervals depending on the width of the river reach. It is important that the spacing between the measured bed particles is consistent, as this will retain the integrity of the method for determining the particle size distribution. It is also important to obtain a suitable sample of at least five stones in the main river channel for each transect. The location and elevation above some datum (such as mean sea-level) of each stone must be recorded as well as the length of at least the middle axis stone.

In addition to a survey of the actual site, it is important that cross-sections including the flood plain are included. A number of cross-sections upstream and downstream of the site should also be surveyed to identify any possible hydraulic controls. The survey of the Thalweg profile should also be extended beyond the site.

In order to measure water depths during flood events, it is recommended that a number of plastic stage pipes be installed along the edges of the site of interested. The data obtained using these pipes can be used to calibrate or develop a stage-discharge relationship for the specific site which can be used to determine both water depth and water slope under particular flood events. **Figure 39** shows the recommended general layout for collecting the necessary data at the site of interest.

Figure 39: General Layout for Gathering Data at the Site of Interest



The data collected at the site of interest must be used to determine the following:

- The relative position and elevation of each stone
- The median diameter of each stone
- The stone size distribution of the reach based on the median diameter of all the stones
- The d_{50} and d_{84} median particle diameter for the reach
- The average bed slope of the reach
- The discharge to depth relationship (i.e. rating curve) for the reach

Not all of the above information is required if the more generic relationship between DRIFT flood class and stream competence or intensity of movement is used. The only information necessary for this is the stone size distribution to give values of d_{50} and d_{84} and the average bed slope.

5.5 Relationship Between Flood Magnitude and Bed Disturbance

This research project developed two methods for determining the relationship between flood magnitude and bed disturbance. The choice of which method is the most appropriate is based on the availability of information and the level of detail required. The first method is a simple empirical relationship between the DRIFT flood classification and the level of total bed disturbance for the reach. The second method is a semi-empirical model which determines the likelihood that an individual stone will move under a given flood event based on a Movability Number that represents the ratio of applied power to required power. By determining the likelihood of movement for all the stones in the reach, it is possible to determine the total level of bed disturbance for the site under the given flood. The advantage of the second method is that it allows for the environmental scientist to consider the differential impact of the movement of different types of bed element in different parts of the river on the level of ecological disturbance.

The first method allows only a very general consideration of the overall impact of bed disturbance and as a result is much quicker and less demanding, but much less detailed than the first. The two models are discussed below, but first a method for determining the depth discharge relationship for the study site is presented. This is necessary as the more detailed model for determining the movement of individual stones is based on maximum depth and the water or energy slope.

5.5.1 Determining the Depth Discharge Relationship

If there is no existing rating curve for the study reach, then it is necessary to develop one for the site based on a combination of theoretical models and observed data. It is recommended that stage pipes be installed to gather data on actual flood events at the site. This data can then be used to develop the rating curve directly or to calibrate a theoretical model.

There are a number of theoretical models that have been developed to determine a depth-discharge relationship. The most common ones are based on simple resistance equations such as Manning and Chezy. These equations, however, do not give good results under conditions of large-scale roughness (i.e. where the flow depth and the particle size are of a similar order) (Bathurst, 1985). To address this, some models have been developed that account for influence of large-scale roughness on flow resistance. The method proposed in this study, and described briefly below, is that developed by Jonker et al. (2002) specifically for cobble and boulder bed rivers.

The flow resistance equation developed by Jonker et al. (2002) is as follows:

$$V = \sqrt{2g}\sqrt{\frac{dS_0}{C_x}} \tag{5.1}$$

with V : average velocity
S_0 : average bed slope
d : particle diameter
C_x : large-scale roughness resistance coefficient

The large-scale roughness resistance coefficient (C_x) was calibrated using laboratory data, but checked against observed data from a number of cobble and boulder bed rivers in the Western Cape. The resistance coefficient is described by the following equation:

$$C_x = 0.5285\left(\frac{R}{d_{50}}\right)^{-2.166} \tag{5.2}$$

with d_{50} : particle size for which 50% is smaller
R : hydraulic radius

It is recommended that these equations be used to determine the likely maximum depth above a particular bed element under the proposed floods. The equation developed in this study, and discussed in the next section, can then be used to determine if a particular bed element is likely to move under a given flood event. By summing up the total number of the measured bed elements that are likely to move it is then possible to determine the stream competence (i.e. the total percentage movement) associated with the particular flood event.

The above stage discharge relationship should be checked using observed data from the stage pipes installed at the specific site of interest. It is therefore important that observations of depth and discharge are made for a number of flood events during at least one flood season prior to the setting of the substrate maintenance flow requirements.

5.5.2 Level of Bed Disturbance Based on DRIFT flood classification

For the two rivers that were studied as part of this research project, a relationship was found between the average level of bed disturbance (i.e. the percentage of the marked stones that moved for a given flood event) and the DRIFT classification for that flood. This relationship can be described by the following equation:

$$I = \frac{e^{34.3.\alpha.DC}}{96.9.\alpha} \text{ with } \alpha = S_0 \frac{d_{84}}{d_{50}} \qquad (5.3)$$

where I = the intensity of movement as a percentage
DC = the DRIFT flood classification
S_0 = the average bed slope
d_{84} = the median stone diameter for which 84% are smaller
d_{50} = the median stone diameter for which 50% are smaller

This relationship will enable scientists to be able to get a first order estimate of the level of disturbance likely to be associated with a particular flood class for cobble and boulder bed rivers. This can then be used to set the required flood magnitude for the desired level of ecological disturbance. It will also enable the practitioner to make a more informed judgement on the impact of having more or less flood of a certain class in the managed flow regime as part of the DRIFT flood classification methodology.

It is important to note that this reach factor (α) is only provisional at this stage. The above relationship is based on a few samples in only two rivers in the Western Cape. The above equation is therefore a proposal for a possible form of universal relationship between the intensity of movement (I), the DRIFT flood class (DC) and the specific reach characteristics (α). Further research and testing of this relationship on other rivers is important before the above relationship can be considered for use in environmental flow assessments and rehabilitation studies.

5.5.3 Level of Bed Disturbance Based on the Incipient Motion of Individual Particles

If more detail is required on the likely disturbance of individual stones (e.g. for a Comprehensive Reserve determination study) then the second model developed as part of this research project could be used. This model looked to define the point of incipient motion in terms of a Movability Number, which represents the ratio of the power made available by the flowing stream to the power required to move the individual stone. The unit stream power (per unit volume) approach, introduced by Rooseboom (1974), has the advantage, over other theories of incipient motion such as the shear stress model developed by Shields (1937), of defining both the transporting capacity of the stream and the effort required to transport material in directly comparable scalar terms. Rooseboom (1998) was also able to use the theory of unit stream power to give mathematical justification for the parameters of the empirically derived Liu diagram of incipient motion for uniform bed material A third advantage of using the theory of unit stream power is that it directly takes into account the absolute roughness of the stream bed.

The unit stream power theory was used to develop the following relationship for incipient motion on beds of non-uniform particle size distribution:

$$\frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} = 0.12 \qquad (5.4)$$

where *D* : flow depth, measured to the top of the stone
d : individual stone diameter measured on the second longest axis
s : energy slope (can use water slope, or even average bed slope)
V_{ss} : Turbulent settling velocity ($V_{ss} = \sqrt{\frac{4(\rho_s - \rho)gd}{3\rho C_d}}$)
k : absolute bed roughness (*k* = minimum of d_{84} or D)
d_{84} : particle diameter for which 84% of particles are smaller
C_d : drag coefficient ($C_d = 0.4$)
ρ : density of water
ρ_s : density of particle
g : acceleration due to gravity (*g* = 9.81)

It is important to note that this relationship was developed using data obtained from only thirteen flood events and from only two streams. The average bed slope of the Molenaars study reach was 0.018 m/m and for the Berg studies reach it was 0.015 m/m. The observed particles were all in the cobble to boulder range with a maximum stone size of just over 1m in diameter. The d_{84} for the Molenaars study reach was 538 mm while the d_{84} for the Berg study reach was 372 mm. The d_{50} for the Molenaars study reach was 248 mm while the d_{50} for the Berg study reach was 205 mm.

It is unclear at this stage if this represents a universal finding for all rivers of non-uniform particle size distribution. To be able to answer this will require the model to be tested on other rivers. The results from the two rivers tested, however, were consistent despite being of different size and having different stone size distribution. Based on this observation it could be hypothesized that the above results will be universal at least in the case of cobble and boulder bed rivers.

5.6 Impact of Bed Disturbance on Aquatic Ecosystems

Some of the results, that may assist in the determination of the required level of bed disturbance to maintain a sustainable aquatic ecosystem in terms of invertebrates in cobble and boulder bed rivers in the Western Cape are discussed below, followed by more general considerations for determining the potential impact on other organisms in other rivers. Full details are presented in the *Ecological Disturbances Report* (WRC report 1441/2/07).

In the Berg River, in 2004, there were two large intra-annual floods during the study period that moved between 25 and 43% of the river bed, and three minor spates (DRIFT Class I and II) that moved less than 3% of bed sediments. The larger floods represented a low and a high DRIFT Class IV flood, and moved all size categories of river bed materials (small cobble through to boulders), but to different degrees. These larger floods are more akin to descriptions of 'disturbance' used in the scientific literature, although the cumulative effect of small floods on population dynamics should not be ignored.

The floods in the Berg River were associated with some 58% decrease in total invertebrate density, cumulative for the two-month period. Nearly all individual invertebrate taxa declined significantly, whilst three mayfly taxa increased in densities on stones over the study period. The large floods on the Berg River appeared to exceed a disturbance threshold for other taxa that were not affected by the smaller floods on the Molenaars River, for example, Simuliidae.

The Berg River study allowed for the effects of stone movement or non-movement during floods to be described, in relation to the magnitude of the disturbance-response by invertebrates. The percentage decrease in total invertebrate density on stones that were unmoved over the whole study period, relative to those that moved in both large floods was 40% and 62% respectively, a difference of some 20%. This result indicates that, despite obvious flood-induced mortality, many taxa were still present in reasonable densities on moved stones - an unanticipated finding. These results also indicate a 'relative refugium' afforded to invertebrates on stable stones. Whilst this was only some 20% for total invertebrates, it was shown to be more or less important for different taxa. It is noteworthy, however, that a number of taxa virtually only survived floods because of the relative refugium of unmoved stones - viz. Leptophlebiidae, most Trichoptera, and the mayfly *Afroptilum* spp. Similarly, *Lithogloea harrisoni*, which appears on the river bed at the start of winter, only increased in population density on unmoved stones.

The responses to floods on both unmoved stones vs. those moved in both large floods are summarised in **Table 16**, for invertebrate taxa which were represented in sufficient densities in order to show patterns. The susceptibility to flow is a measure of the extent to which the series of floods reduced population densities.

These results add to the current understanding of how floods may affect ecological processes regarding species interactions, since they clearly demonstrate substantial differences in the disturbance-response between different and potentially competing species. However, this study was not able to obtain sufficient data to develop a clear relationship between a significant level of ecological disturbance and the percentage of bed movement or more importantly the likely impact of not having a certain percentage of bed movement.

Table 16: Summarised Species-specific Responses to Winter Floods in the Berg River, 2004, Showing the Relative Refugium from Flood Mortality Afforded by Unmoved Stones

SPECIES / TAXON	UNMOVED STONES		STONES MOVED IN BOTH LARGE FLOODS	
	Repeat-sampled	Additional	Repeat-sampled	Additional
No relative refugium offered on unmoved stones				
Demoreptus capensis	↓↓↓	↓↓	↑↑↑	↑↑↑
Notonemouridae	↓	↓	≈	↑
Simulium spp.	↓	↓↓	≈	≈
Demoulinia spp.	↓↓↓	↓↓↓	↓↓↓	↓↓↓
Cheumatopsyche afra	↓↓↓	↓↓↓	Not present in Baseline	
Tanypodinae	↓↓↓	↓↓↓	↓↓↓	↓↓↓
Orthocladinae	↓	↓	↓	↓
Elmidae adults	↓↓	↓↓↓	↓↓↓	↓↓
Elmidae larvae	↓↓	↓↓	↓↓↓	↓↓
Low relative refugium offered on unmoved stones				
Cheumatopsyche maculata	↓↓↓	↓↓	↓↓↓	↓↓↓
Athripsodes bergensis	↓↓	↓↓↓	↓↓↓	↓↓↓
Afronurus sp.	↓↓↓	↓↓	↓↓↓	↓↓↓
Aprionyx spp.	↓↓	↓↓↓	↓↓↓	↓↓↓
Chironomini	≈	≈	≈	↓
Baetis spp.	↓	≈	↓	↓
Hydrachnellae	↓	↓	↓↓	↓
Euthraulus elegans	↓↓	↓↓	↓↓↓	↓↓↓
Chimarra sp.	↓↓↓	↓	↓↓↓	↓↓↓
Afronurus harrisoni	↓	↓↓↓	↓↓	↓↓↓
Tanytarcini	↓↓	↓	↓↓↓	↓↓
Moderate to high relative refugium offered on unmoved stones				
Lestagella penicillata	↓	↓	↓↓↓	↓↓↓
Helodidae	↓	↓	↓↓↓	↓↓↓
Afroptilum spp.	↑	↑	↓↓↓	↓↓↓
Lithogloea harrisoni	↑↑↑	↑↑↑	↓	≈
Note: Susceptibility to flow is based on percentage reduction in population density, and provided within categories of percentages. These categories are as follows: ≈- no change (± 24% increase or decrease); ↓ (25 - 69% decrease); ↓↓ (70 - 84% decrease); ↓↓↓ (85 - 100+% decrease). Arrows facing upwards indicate increases in density.				

The results of this research project indicated that there was no clear relationship between ecological disturbance, measured in terms of invertebrate population reductions, and increasing measures of applied power or shear stress experienced at the bed level. However, larger floods were associated with population losses for most species, even where substrata did not move.

Furthermore, there was a significant relationship between stones that moved during a particular flood event and those that did not move, in terms of the magnitude of the disturbance-response of different species. This leads to the hypothesis that during a flood event many organisms are able to find refuge behind or under a stone and as such are not disturbed by the increasing level of applied power or shear stress. At some point, however, the level of applied power or shear stress reaches a critical value and the stone moves. This movement has been shown to have a more substantial impact on the aquatic ecosystem, and importantly, different impacts on the interacting species within river ecosystems.

The preliminary species-specific results may aid in setting flow requirements in rivers, during Environmental Water Requirements studies, particularly where there is evidence of species interactions, or where pest species (Chironomidae, Simuliidae) may proliferate under low disturbance regimes. Disturbance regimes then can be set to achieve specific aims with regard to the regulation of populations of particular species, within a regulated flow regime.

It is recommended, therefore, that the practitioner tasked with developing the significant level of ecological disturbance considers the specific conditions of their location and make use of whatever additional information is available to assist in deciding what the required level of ecological disturbance is and hence what is the required amount of bed particle disturbance required is. It is recommended that an environmental scientist with specific knowledge of the aquatic ecosystems of the identified site perform this task, but that it can be done in conjunction with other experts as part of the general process for determining environmental flow requirements.

5.7 Selection of Substrate Maintenance Flow Requirements

The information generated according to the recommendations in the above sections will aid in the decision making on what the required substrate maintenance flows should be. There are many factors that influence this decision. The level of disturbance is only one factor that must be balanced with other environmental requirements such as channel maintenance or the requirements for downstream features such as wetlands and estuaries. An important part of the decision making process is the likely trade-off between the downstream environmental requirements and the economic considerations in terms of the capacity of outlet structures to be able to deliver the required flow, and the value of this water if made available to other users.

The final decision on the appropriate flood regime to ensure a sustainable aquatic ecosystem must be taken in a workshop setting with input from all parties concerned. The workshop environment must be used to resolve any potential trade-offs between the environmental flow requirements and the economic considerations for making these releases. The information gained from the above method for determining the substrate maintenance flows can only provide a certain degree of technical input into the debate. The final decision will be informed by this information, but will ultimately depend on expert judgement and socio-political and economic factors, which must include the significance of a healthy and sustainable aquatic ecosystem.

6. CONCLUSIONS AND RECOMMENDATIONS

The key objective of this phase of the research project was to develop a theoretically based hydraulic model that will address the relationship between discharge and substrate disturbance in cobble and boulder bed rivers. This has been met through the collection of data on stone movement from a total of thirteen flood events observed across two different study sites and the development of a theoretical mathematical model to describe incipient motion of individual bed particles in a cobble and boulder bed rivers, and an empirical model that relates the level of bed disturbance or the intensity of movement to the DRIFT class of a specific flood event.

In addition, this report meets one of the other aims of the Study, which was to develop Guidelines for the determination of substrate maintenance flows in cobble and boulder bed rivers. The proposed Guidelines are outlined in a separate section of this Report and draw on the key findings from a second Report on ecological disturbance levels, prepared as part of this Study.

6.1 Incipient Motion in Cobble and Boulder Bed Rivers

The first model was concerned with the threshold of movement for individual stones. This was developed in order to gain a better understanding of the forces experienced by a particular stone during a flood event so that these could be related to the level of disturbance in the invertebrate and periphyton communities in a subsequent phase of the project. It was decided that this model would be based on the Movability number in the Liu Diagram, as this is an dimensionless term that is often used to describe incipient motion and the Liu Diagram is familiar to most people interested in stream hydraulics. The Movability Number was representative of the ratio of applied power to required power. The model was calibrated using the observed data and found to result in a constant term equal to that derived by Rooseboom (2000) to describe incipient motion on a uniform bed. The model was found to give results as good, if not better, than a calibrated shear stress model.

The second model was developed in order to investigate the relationship, if any, between the DRIFT flood classification system and the level of bed disturbance. This would be useful in determining the impact that the reduction in the number of a certain class of flood under a managed flood regime would have on the disturbance of the bed particles and hence on the sustainability of the benthic communities. This model would therefore speak directly to the current system for determining environmental flow requirements. A simple empirical model was selected for this purpose and this was calibrated with the data collected during the thirteen flood events experienced at the two study sites.

6.2 Guidelines for Substrate Maintenance Flows

Guidelines for the use of the hydraulic model for incipient motion in cobble and boulder bed rivers have been prepared and included in this Report. These Guidelines give a brief outline to the steps required to determine substrate maintenance flows, and provide some guidance on what is required for each step. It is important to note that these are proposed guidelines only and that they must be incorporated into the broader aims and objectives of Reserve determination or other EFR studies. The proposed Guidelines draw on the key findings from a second report on ecological disturbance levels prepared as part of this Study.

6.3 Recommendations for Further Work

It is important to note that the models and guidelines presented in this Report are based on a limited sample of thirteen flood events in two rivers in the Western Cape. It is important that the recommendations made in this Report are tested on other rivers and for other flood events, before they can be fully developed. These and other research recommendations with regards to the development of the hydraulic model for predicting the movement of individual stones and the overall bed disturbance due to specific flood events are listed below:

- Further investigations into reduction in transport capacity due to the presence of bed forms in cobble and boulder bedded rivers, in addition to the influence of non-uniform bed material.

- A study of the equilibrium distribution of stone sizes in cobble and boulder bedded rivers with particular reference to the presence of bed forms such as clusters of larger stones with smaller stones located inside.

- Developing a better understanding of the mechanisms for energy dissipation in sheltered areas of the bed through detailed field observations and possible laboratory experiments and the impact that this will have on the incipient motion of stones in these sheltered hollows.

- Investigate ways of determining absolute bed roughness (k) and energy slope (s) at particular points where stones are located on the bed of cobble and boulder bed rivers.

- Analysis of the structure of stable bed forms to determine if these can be identified and quantified in a study reach and the relevance that this will have on determining the bed roughness and the amount of refugia available for stream ecology.

- Further study is required to confirm the proposed empirical relationship between the intensity of movement and the DRIFT flood class. In particular, the use of the reach characteristic term (α) needs to be tested on other rivers.

Further recommendations with regards to the determination of significant levels of disturbance of invertebrate assemblages is discussed in the second Report prepared as part of this study, which can be obtained from the Water Research Commission of South Africa.

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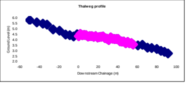
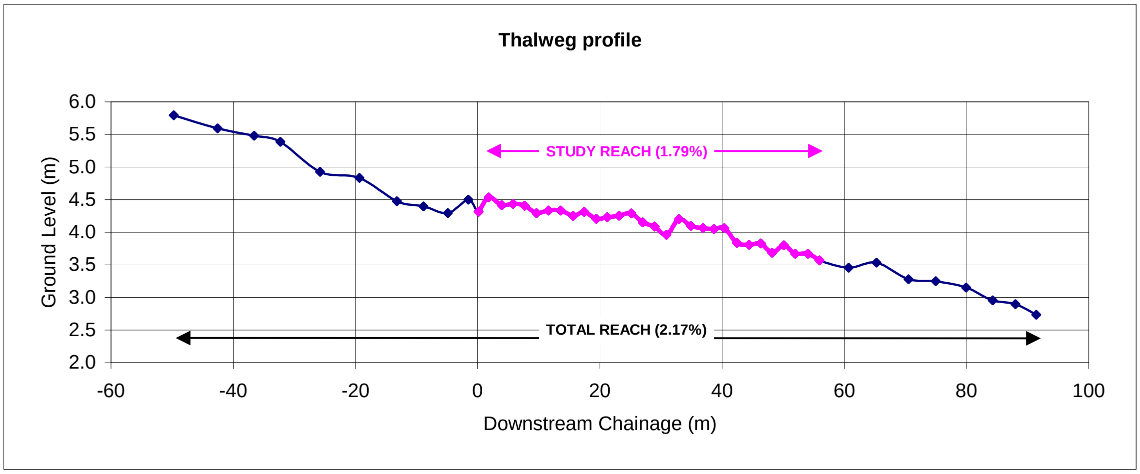
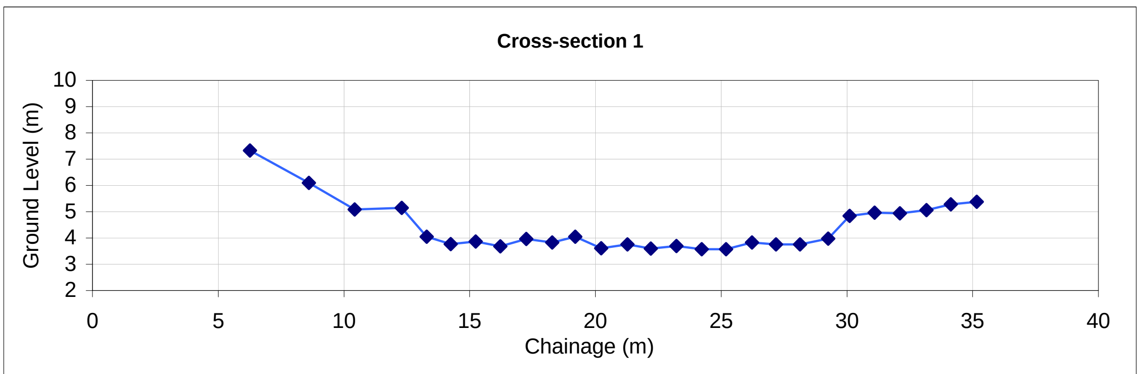
Appendix A: Details of Study Sites

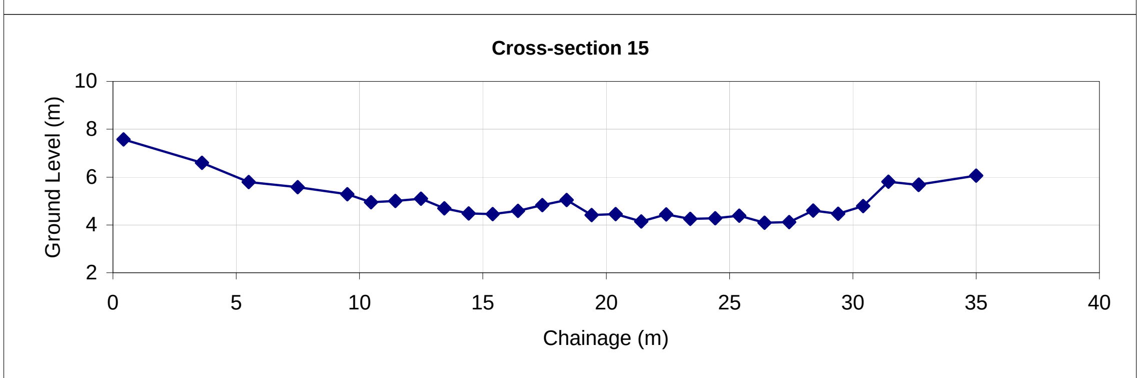


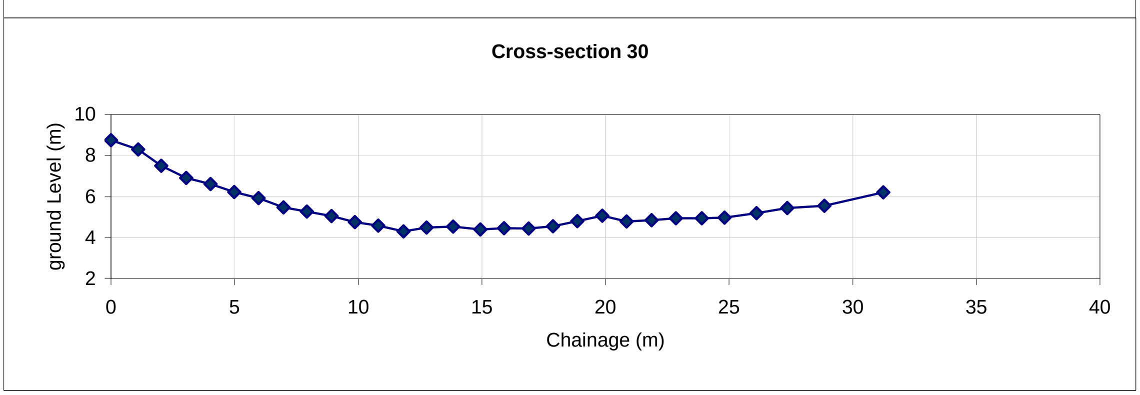
HYDRAULIC MODEL: APPENDIX 1

Figure A1a: Molenaars Study Site: Thalweg and Sample Cross-sections









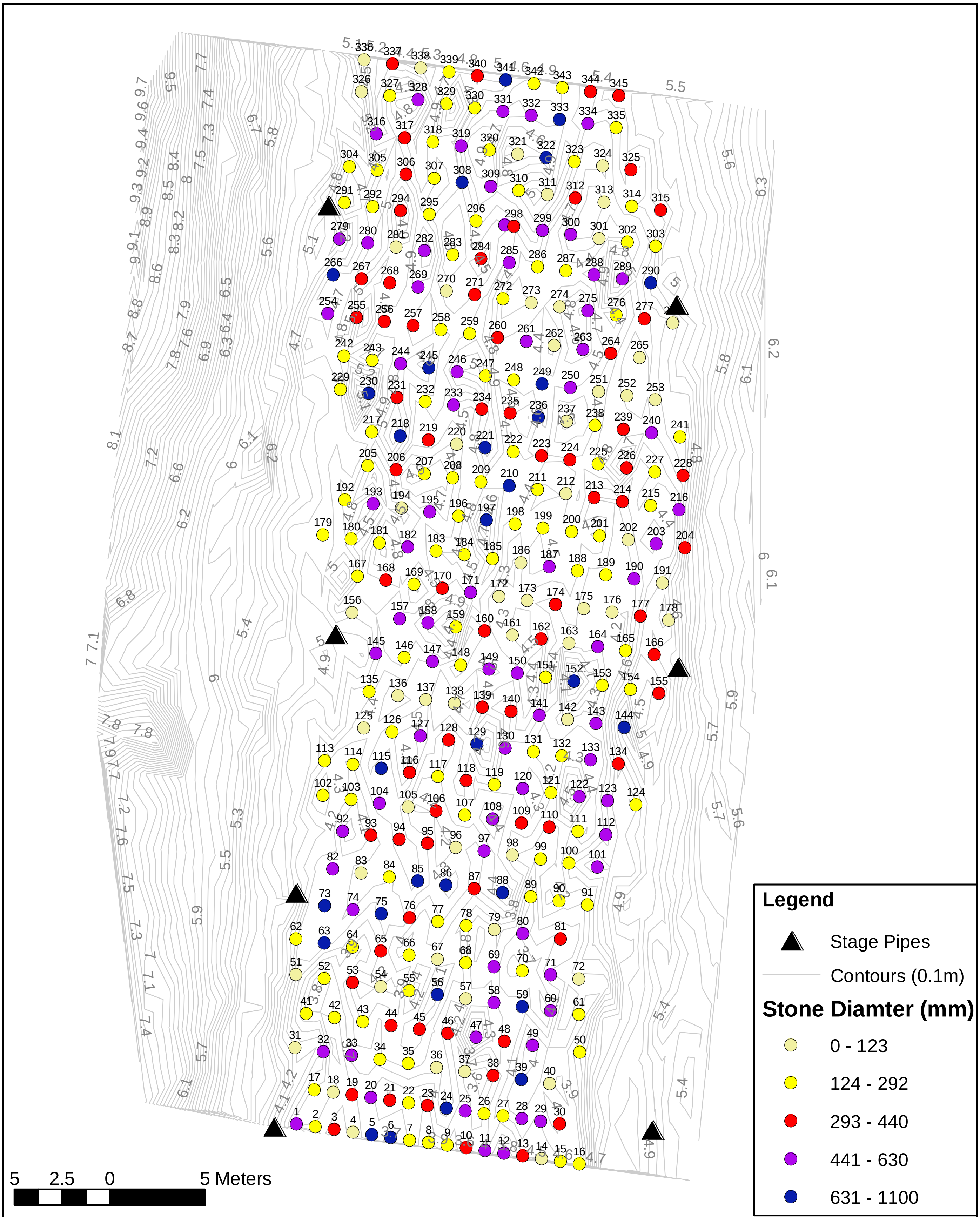


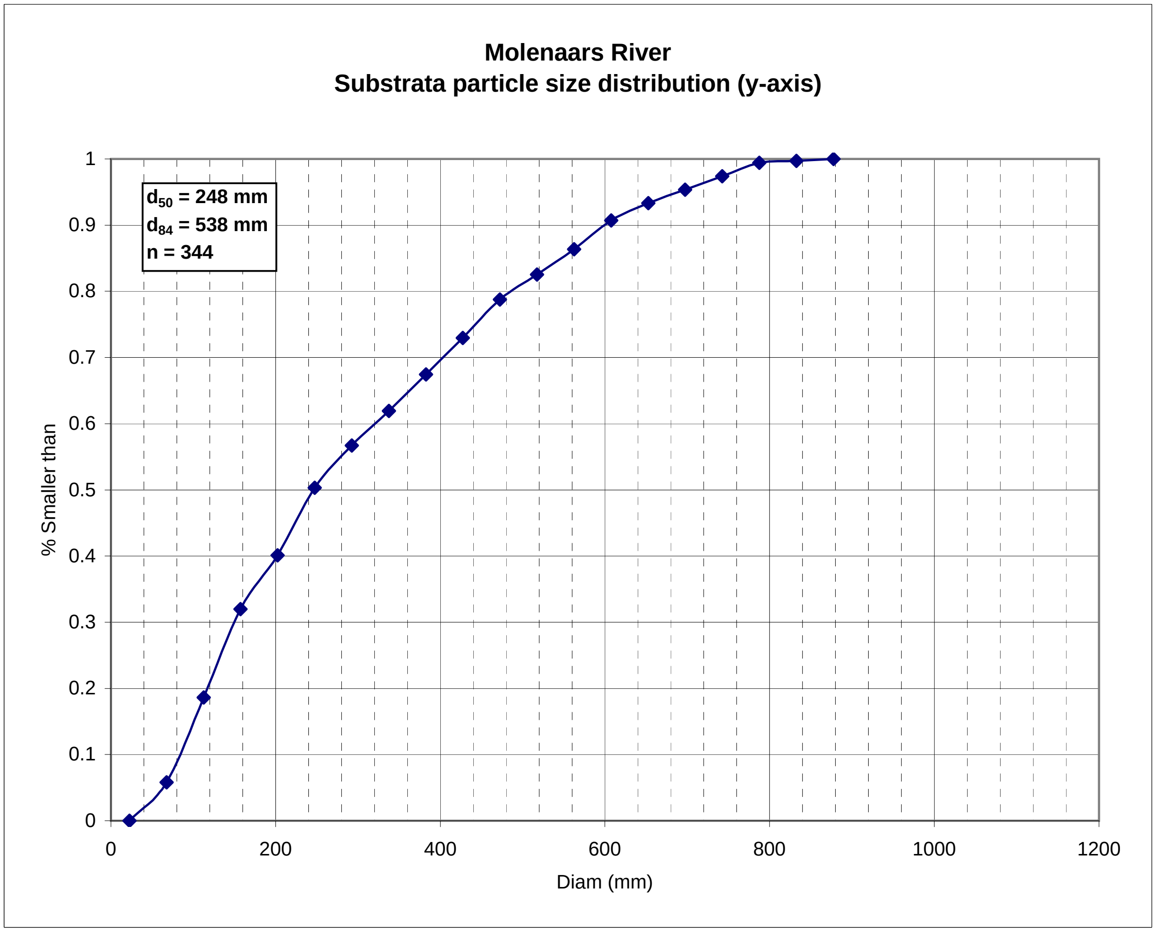
Figure A1b
Study Site Set Up
Molenaars River

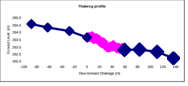
WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

HYDRAULIC MODEL: APPENDIX 1

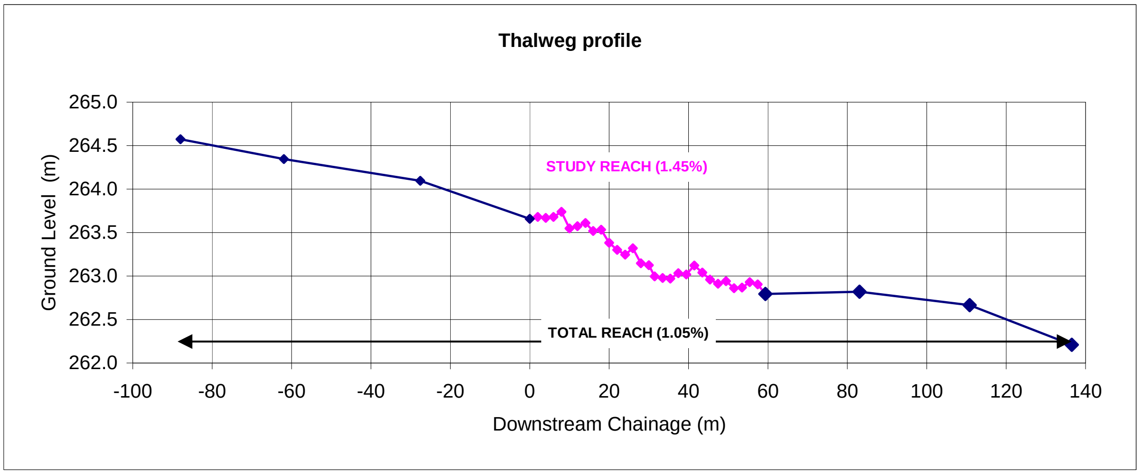
Figure A1c: Molenaars Study Site: Partical Size Distribution

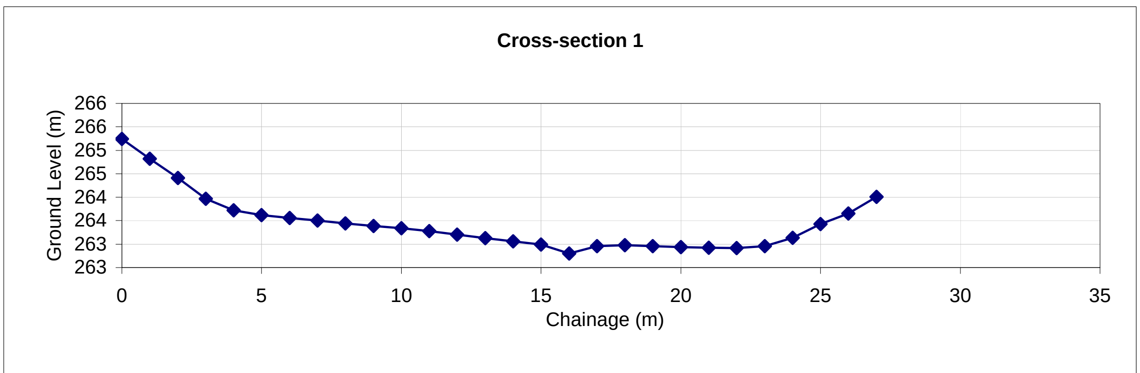


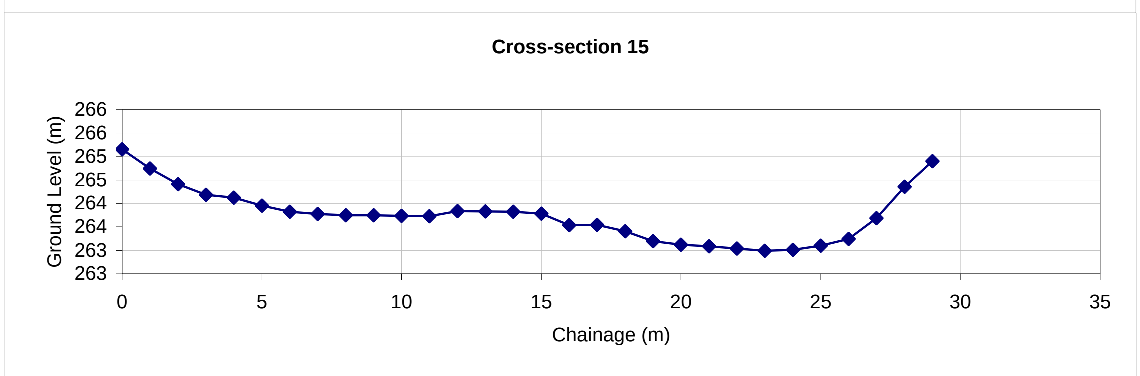


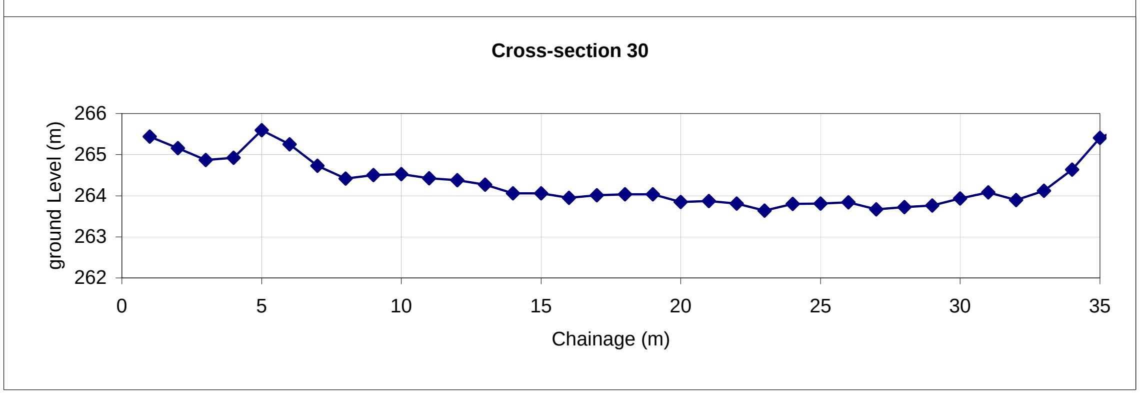
HYDRAULIC MODEL APPENDIX A - 2

Figure A2a: Berg River Study Site: Thalweg and Sample Cross-sections









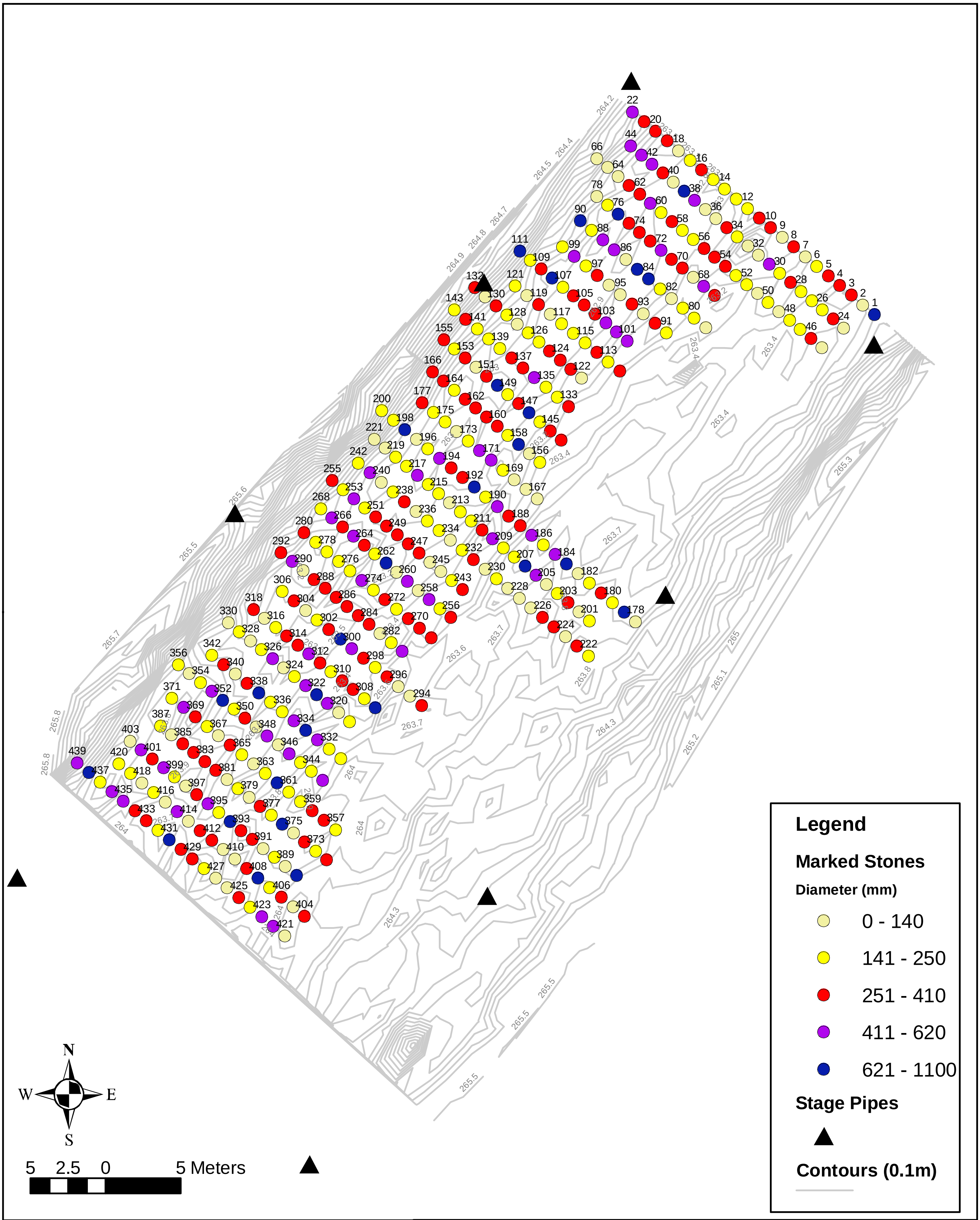


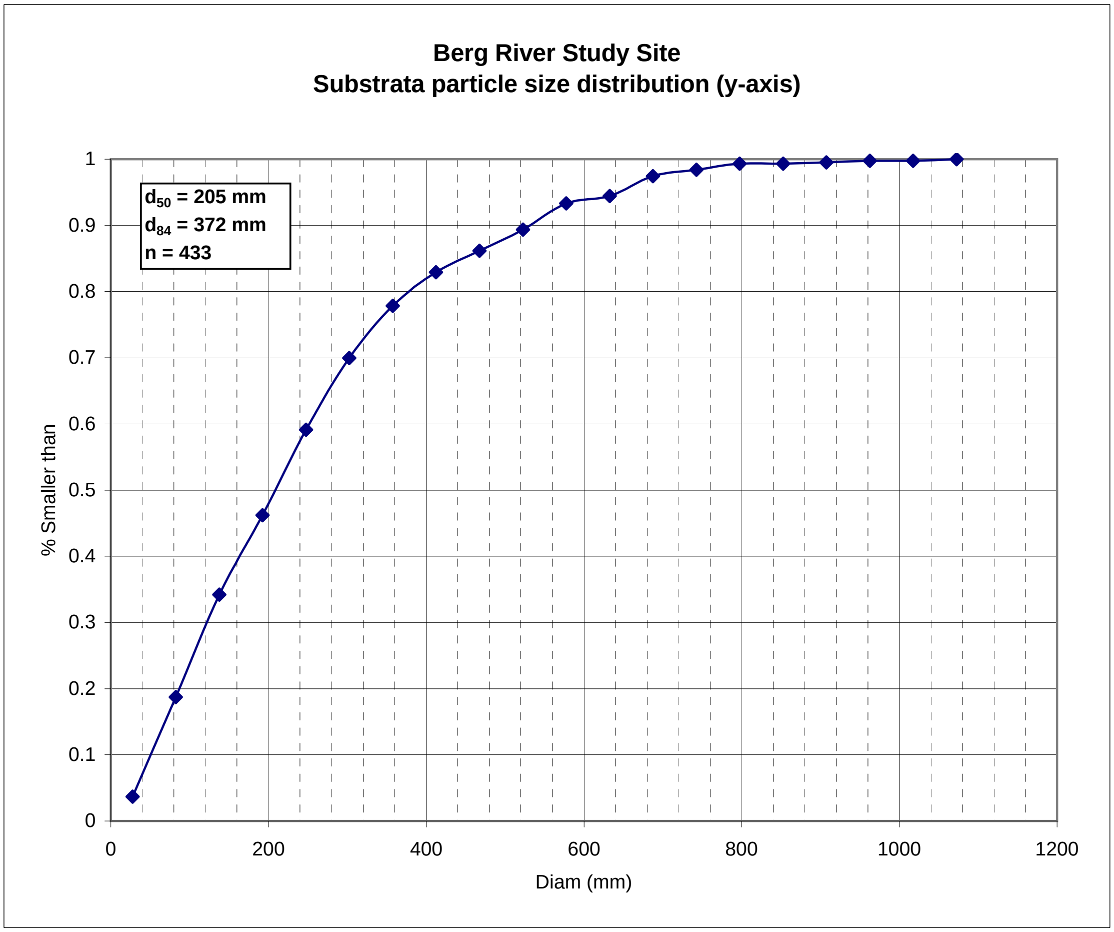
Figure A2b
Study Site Set Up
Berg River

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

HYDRAULIC MODEL - APPENDIX A - 2

Figure A2c: Berg River Study Site: Partical Size Distribution



Appendix B: Base Flow Conditions

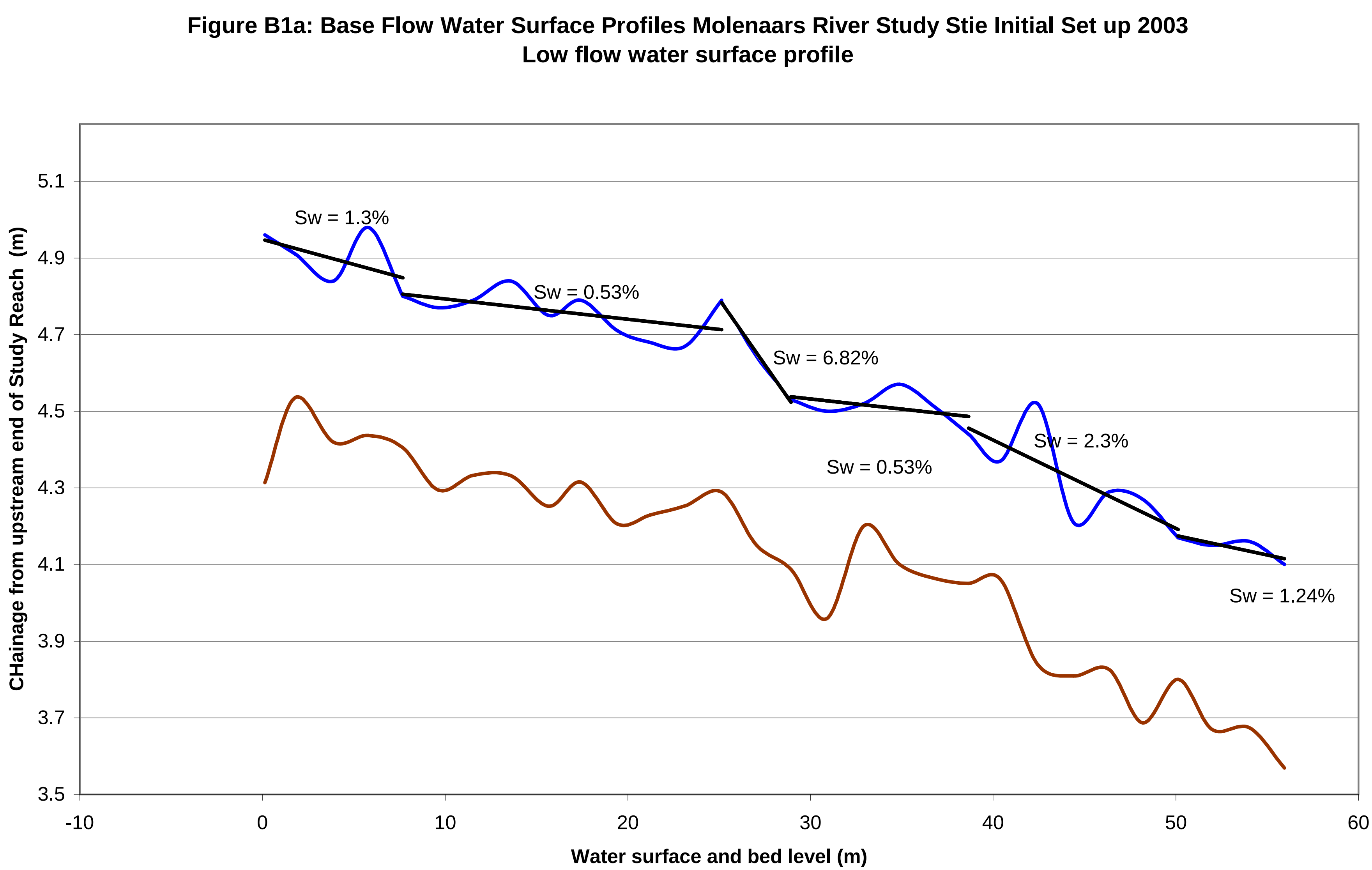


Figure B1a: Base Flow Water Surface Profiles Molenaars River Study Stie Initial Set up 2003
Low flow water surface profile
CHainage from upstream end of Study Reach (m)
Water surface and bed level (m)
Sw = 1.3%
Sw = 0.53%
Sw = 6.82%
Sw = 2.3%
Sw = 0.53%
Sw = 1.24%
5.1
4.9
4.7
4.5
4.3
4.1
3.9
3.7
3.5
-10
0
10
20
30
40
50
60

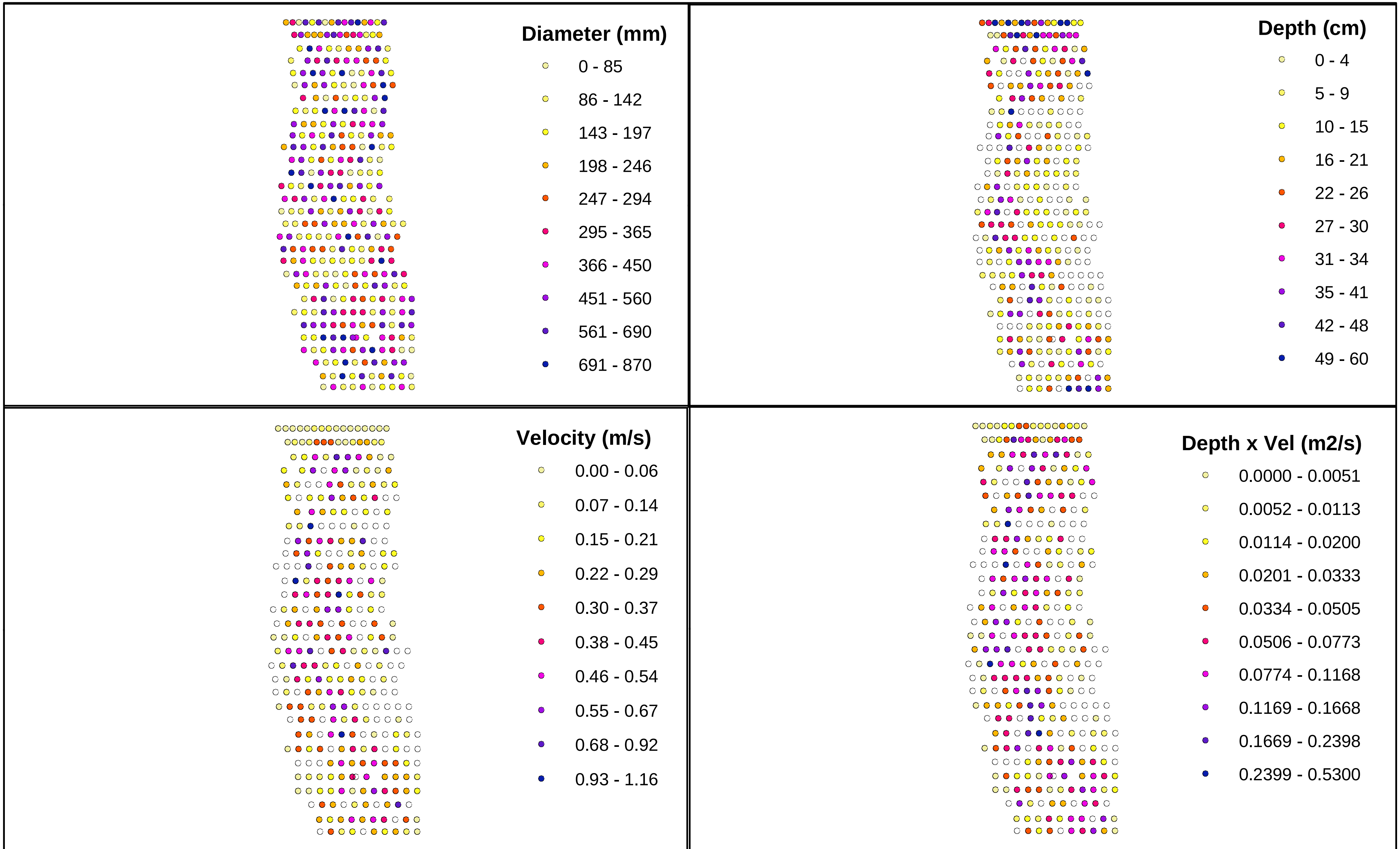
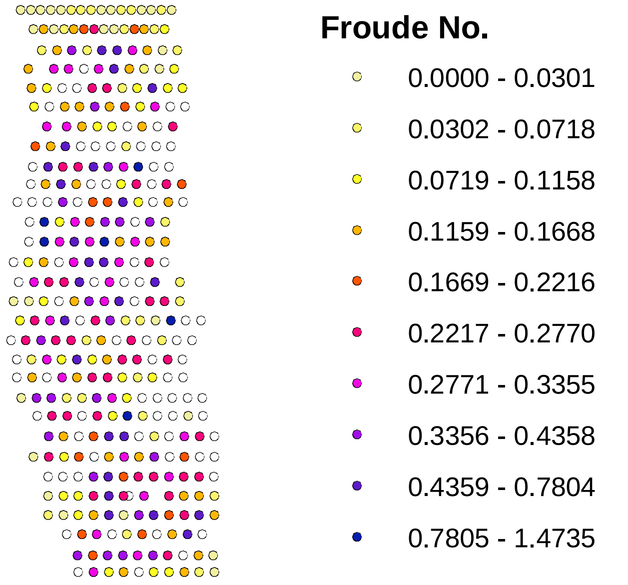
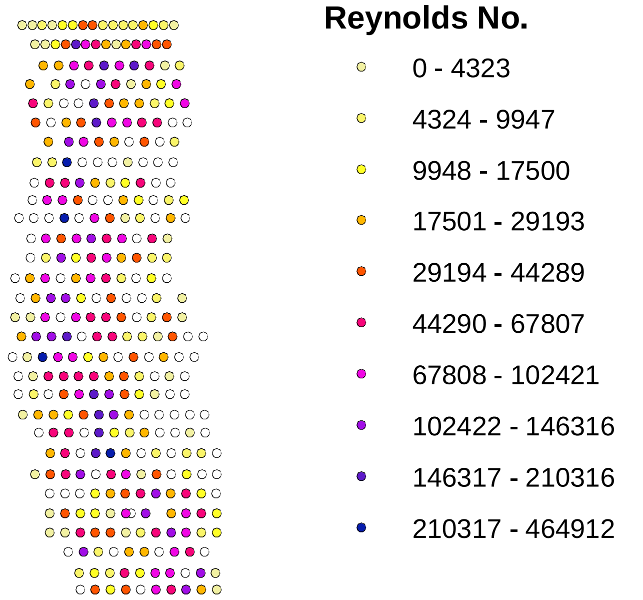


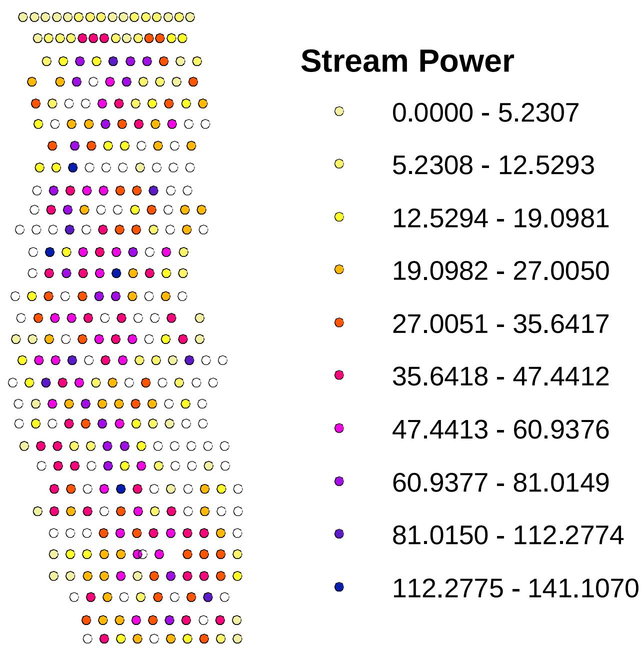
Figure B1b
Base Flow Conditions
Molenaars Study Site
2003

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers:
Ecological and Hydraulic Considerations

Water Research Commission







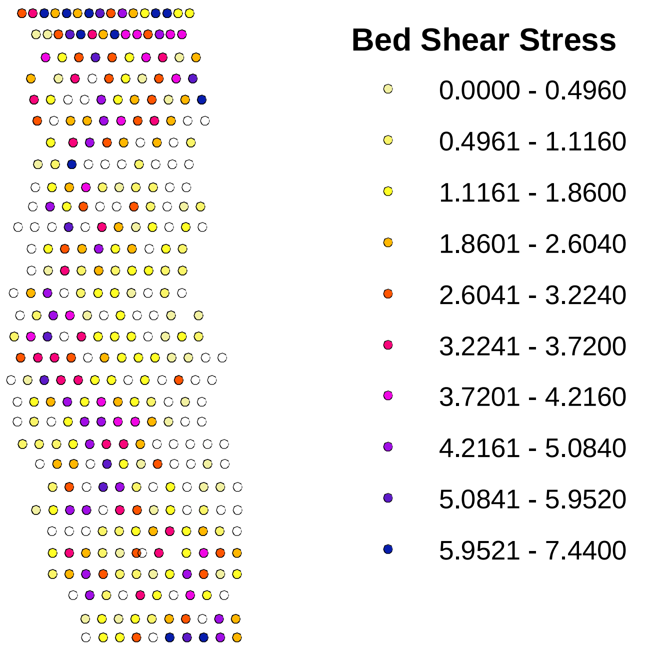


Figure B1c
Base Flow Conditions
Molenaars Study Site
2003

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

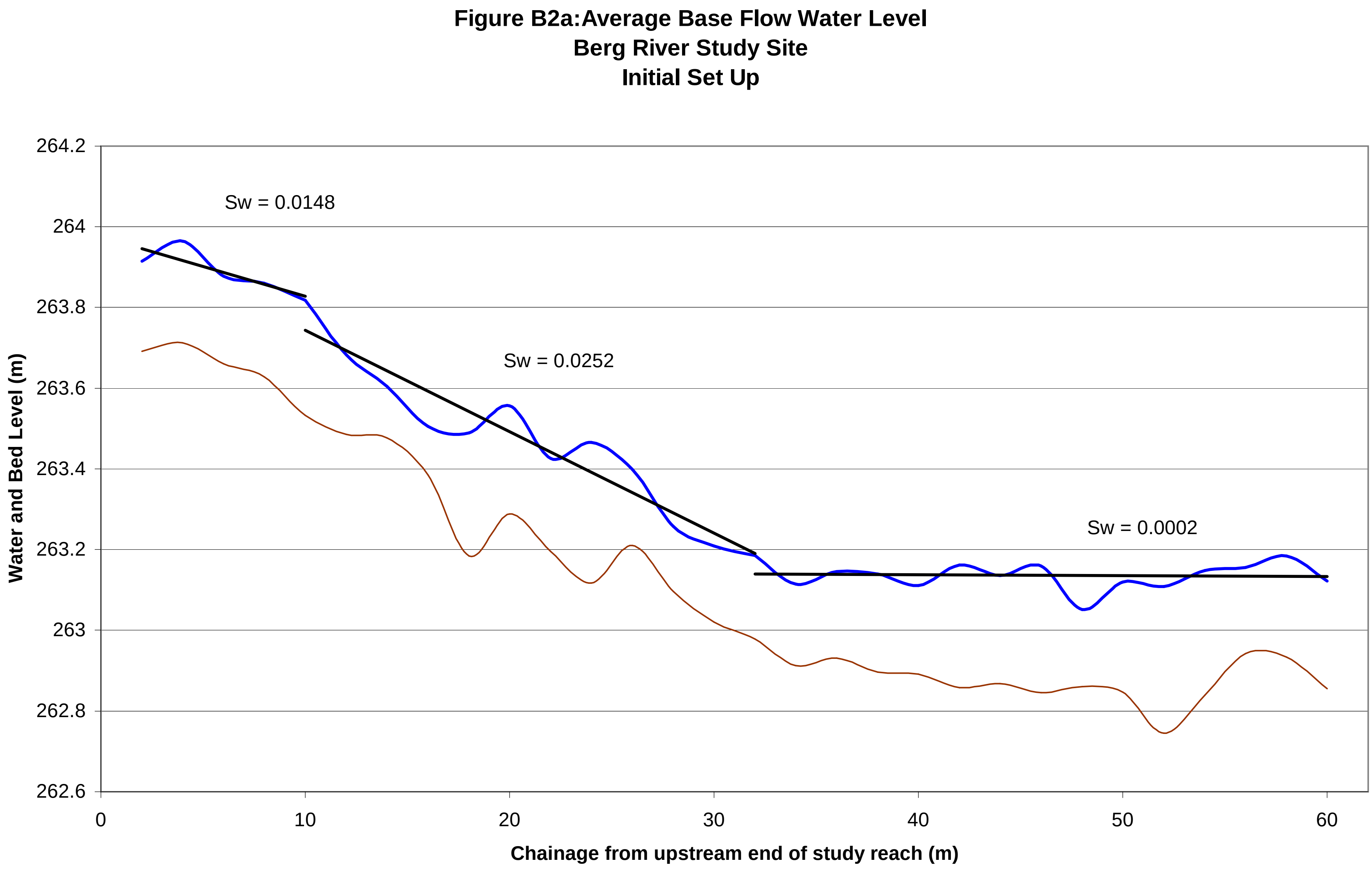


Figure B2a:Average Base Flow Water Level
Berg River Study Site
Initial Set Up
Sw = 0.0148
Sw = 0.0252
Sw = 0.0002
264.2
264
263.8
263.6
263.4
263.2
263
262.8
262.6
0
10
20
30
40
50
60
Water and Bed Level (m)
Chainage from upstream end of study reach (m)

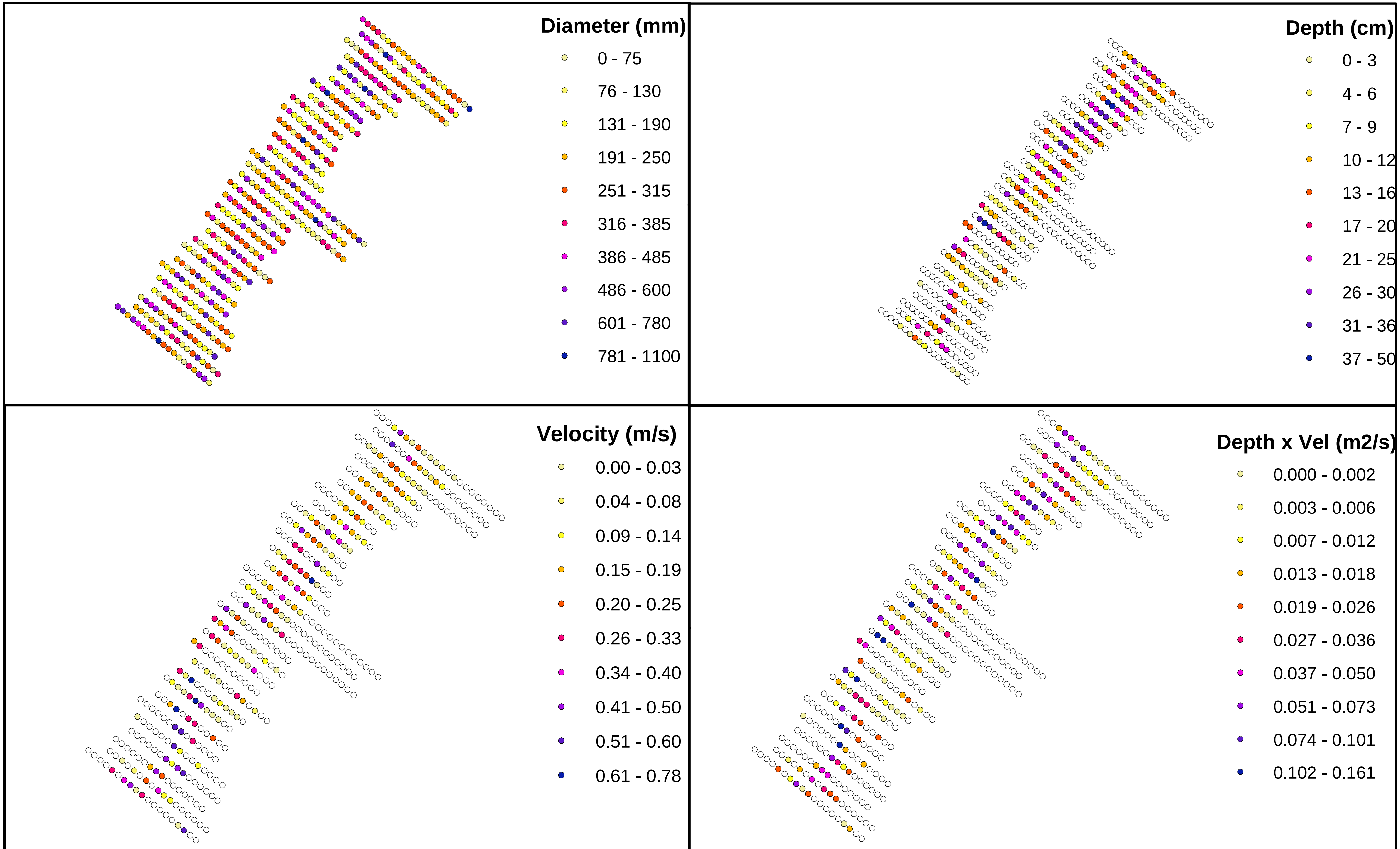


Figure B2b
Base Flow Conditions
Berg River Site
2004

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

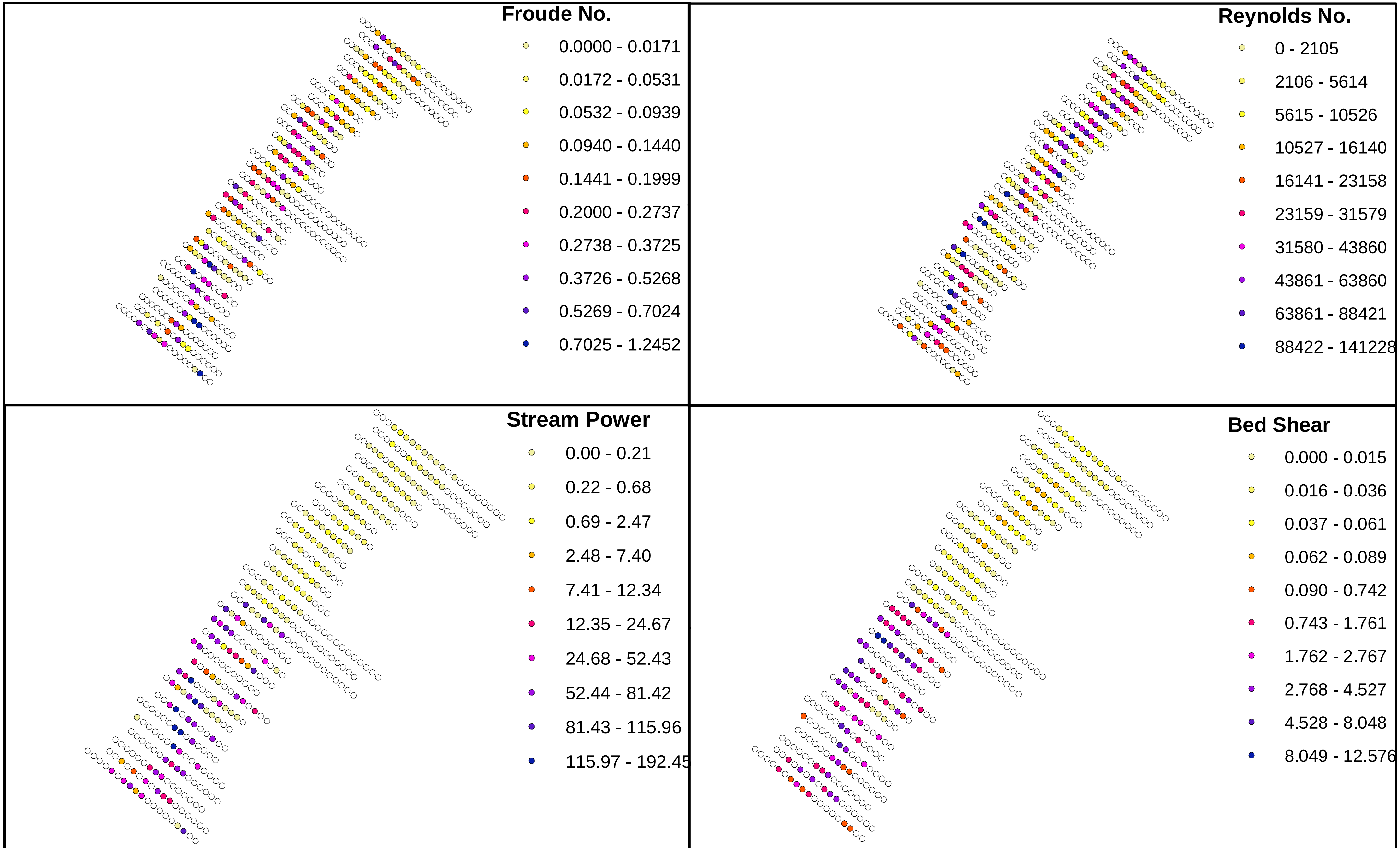


Figure B2c
Base Flow Conditions
Berg River Study Site
2004

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The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

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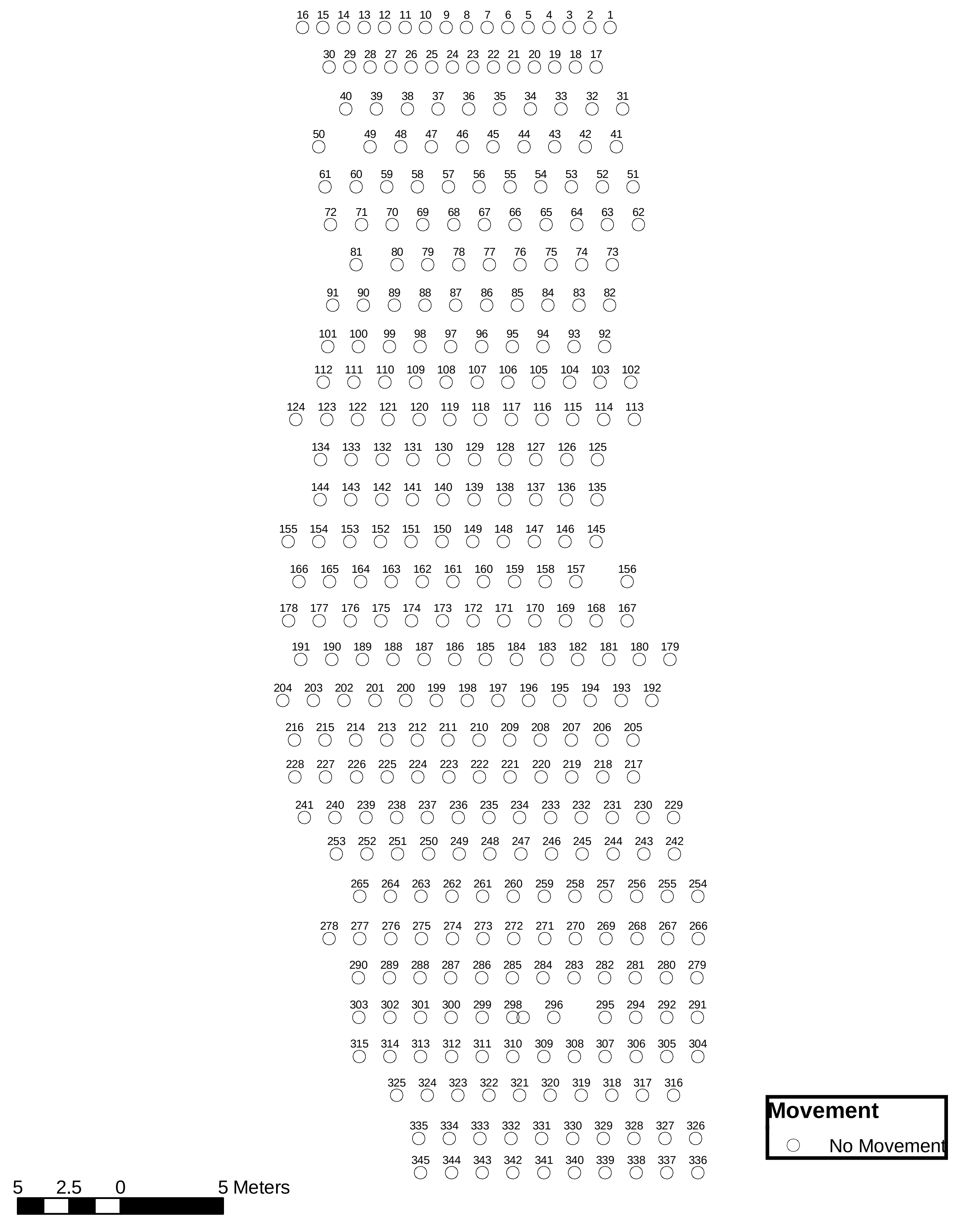
Appendix C: Field Notes from Flood Event Data Collection

Note: These reports are available only on the CD enclosed at the back of this report.

Appendix D: Stone Movement for Individual Flood Events

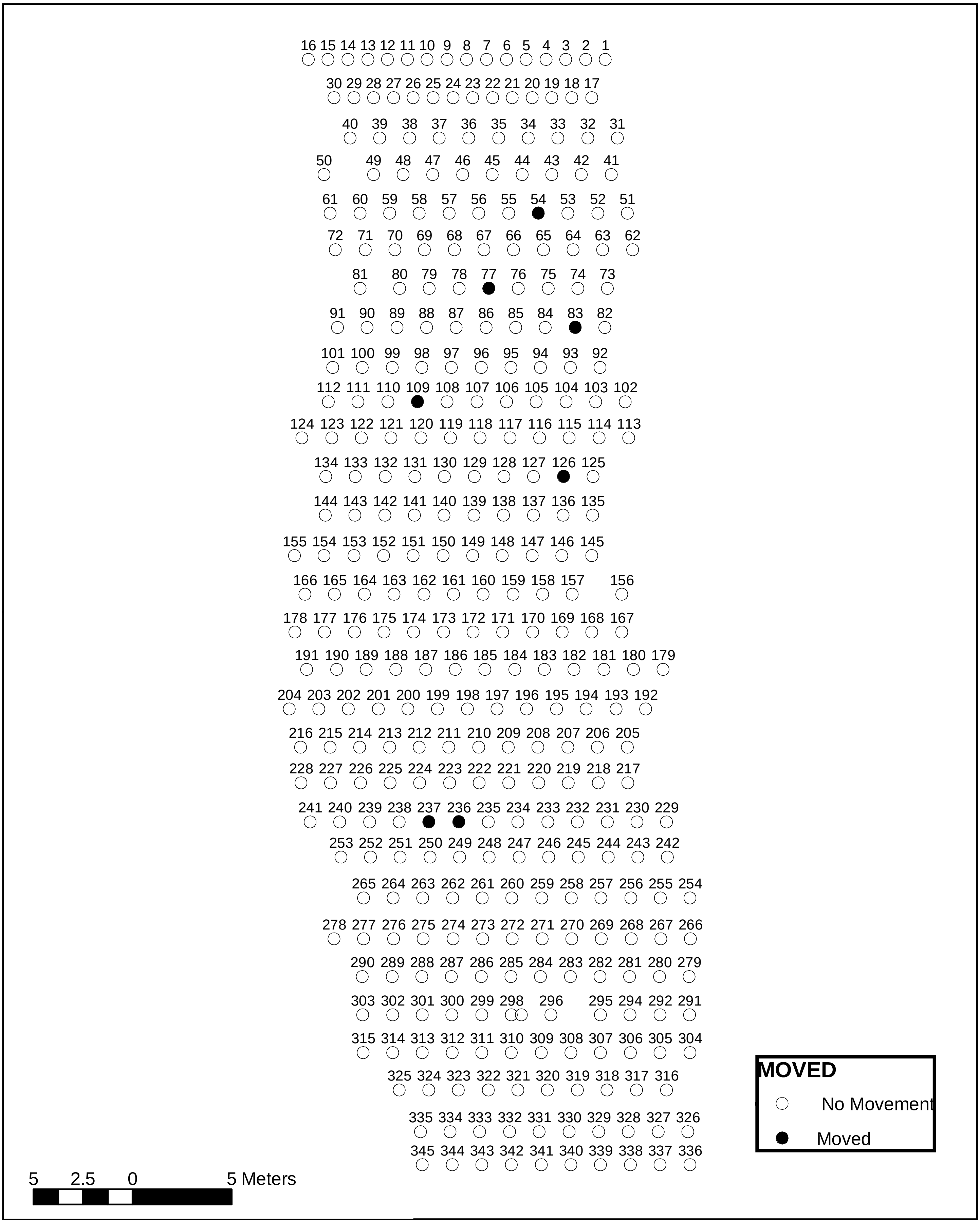


Molenaars River 2003
Stone Movement

Flood 1

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

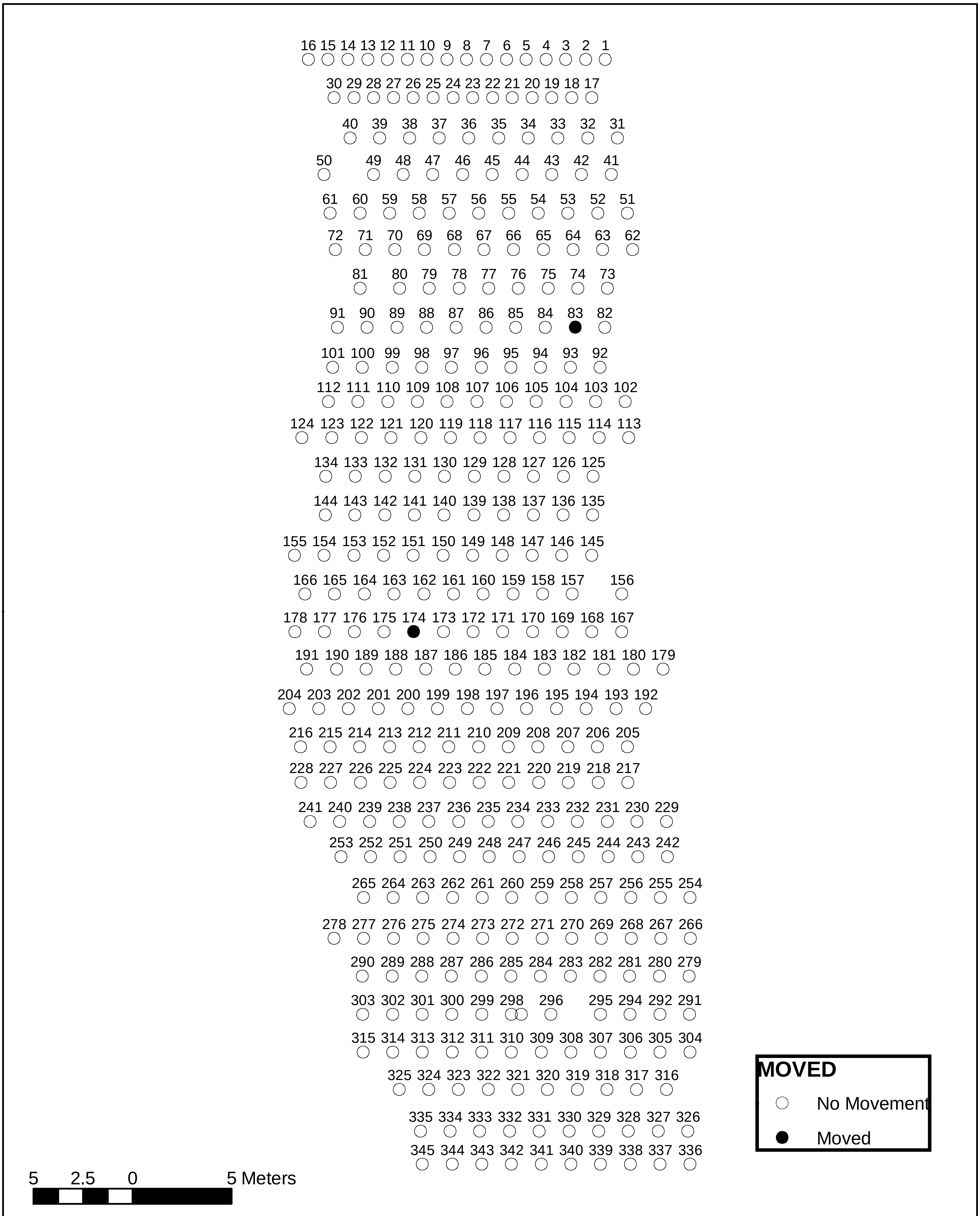


Molenaars River 2003
Stone Movement

Flood 2

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

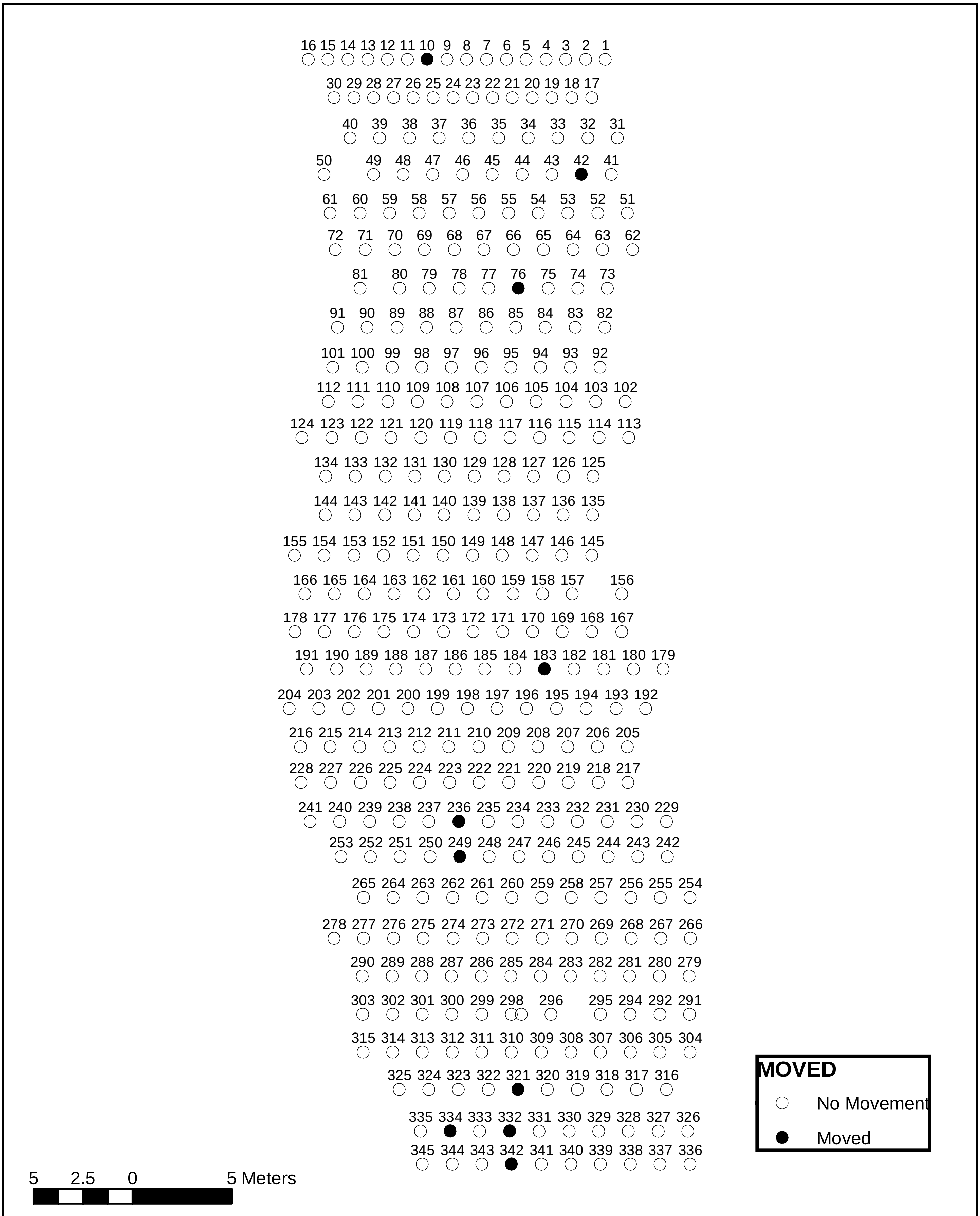


Molenaars River 2003
Stone Movement

Flood 3

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

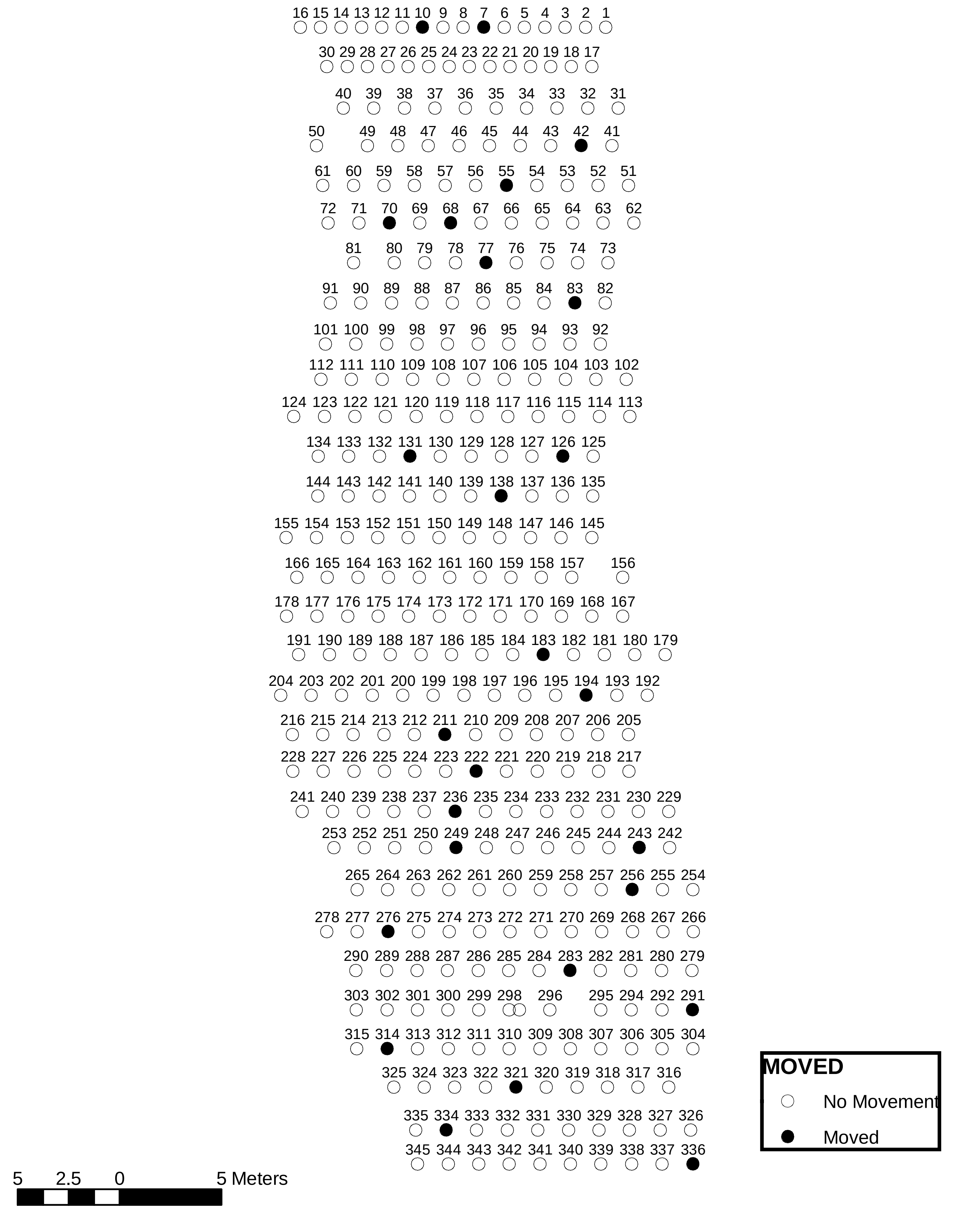


Molenaars River 2003
Stone Movement

Flood 4

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

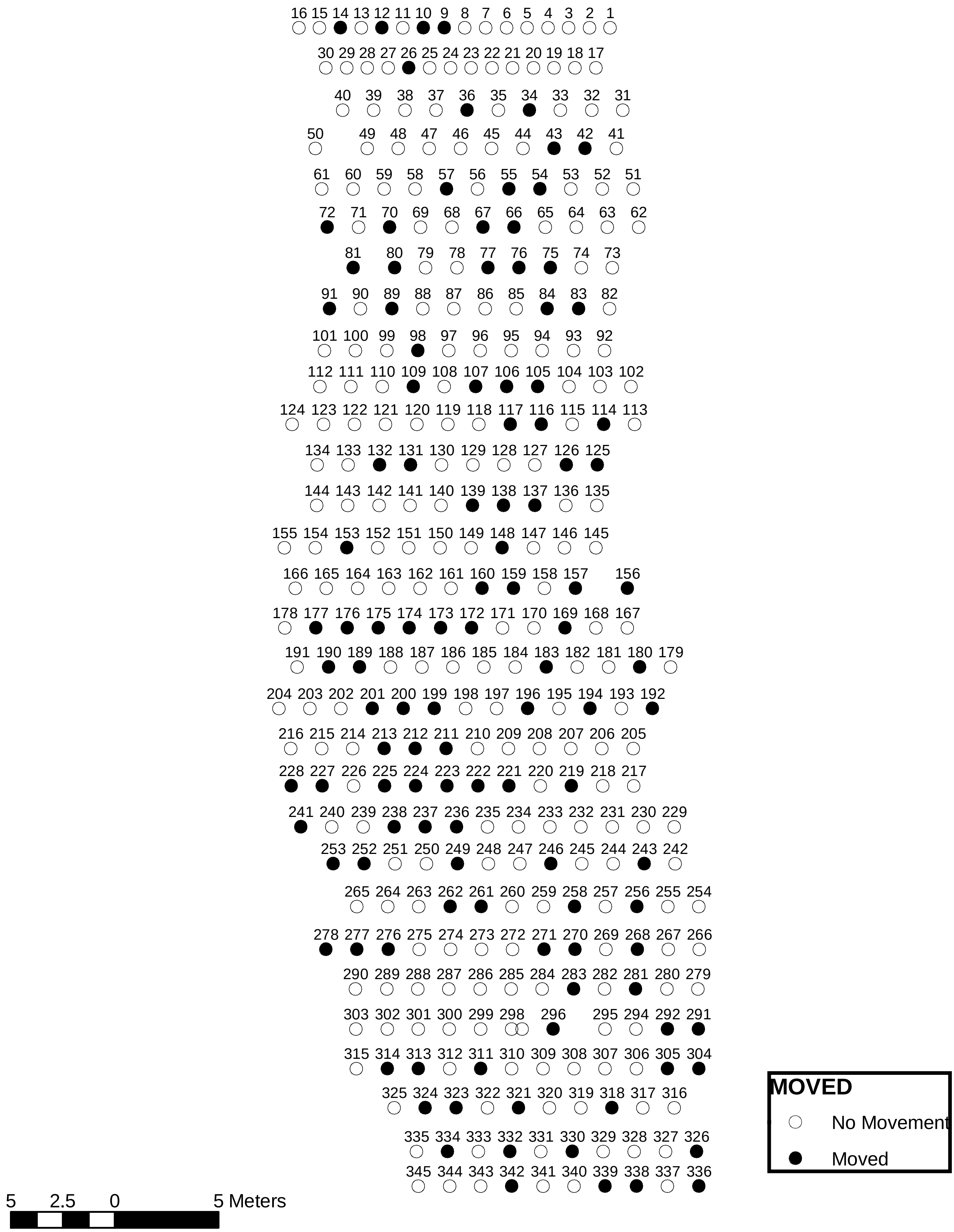


Molenaars River 2003
Stone Movement

Flood 5

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

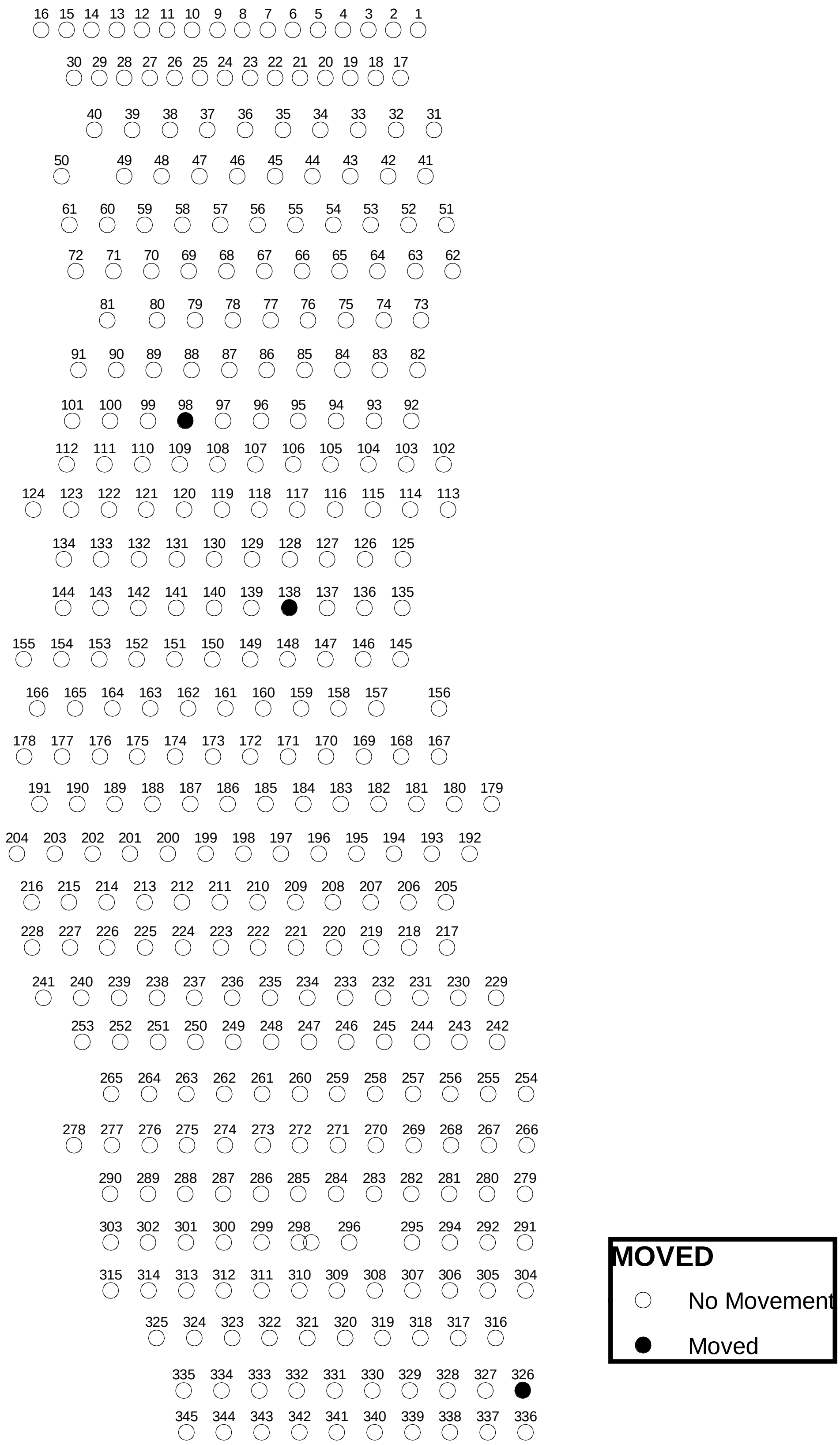


Molenaars River 2003
Stone Movement

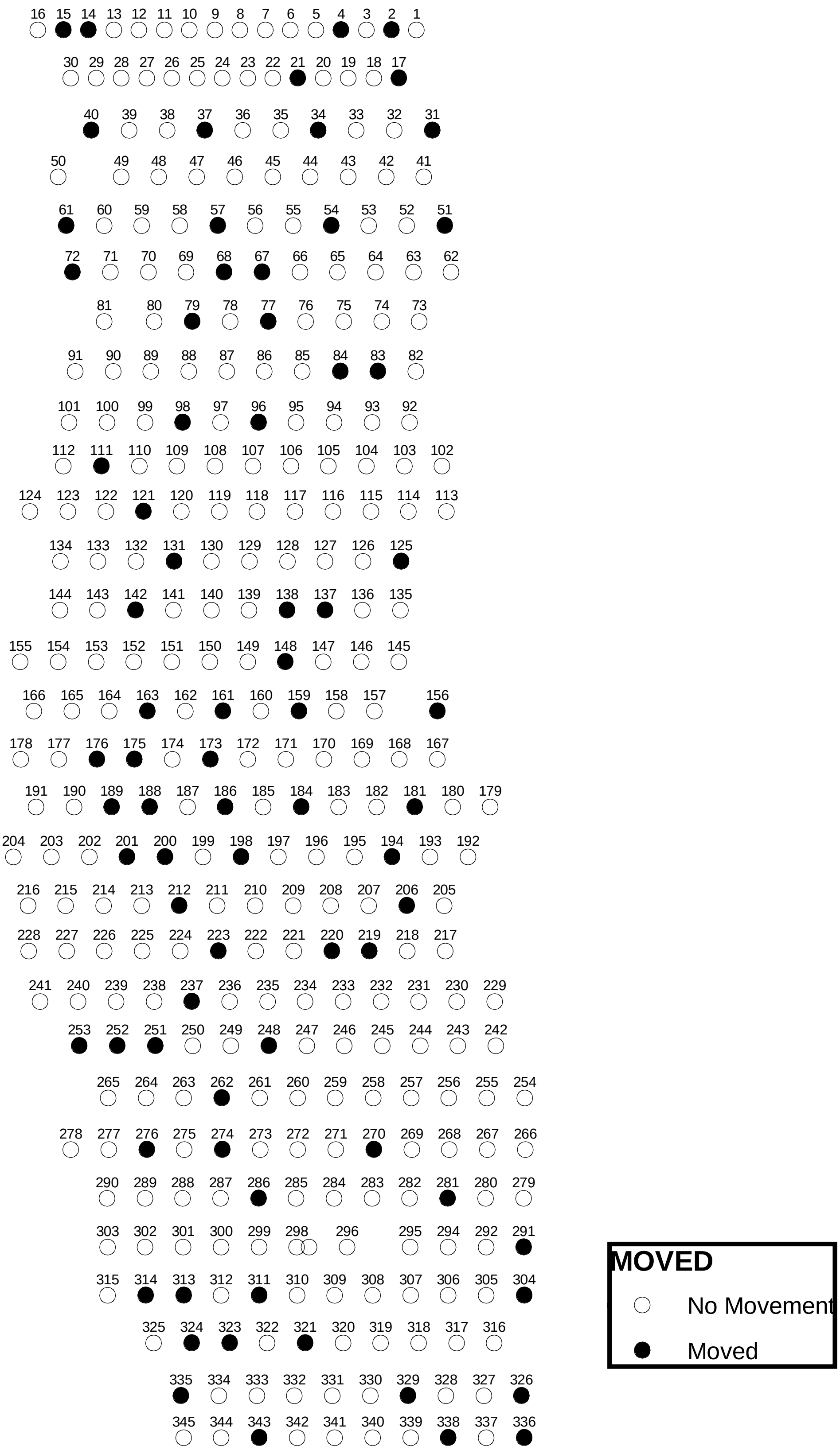
Flood 6

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission



Molenaars River 2004 Stone Movement Flood 1	WRC K5/1411 The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations	Water Research Commission

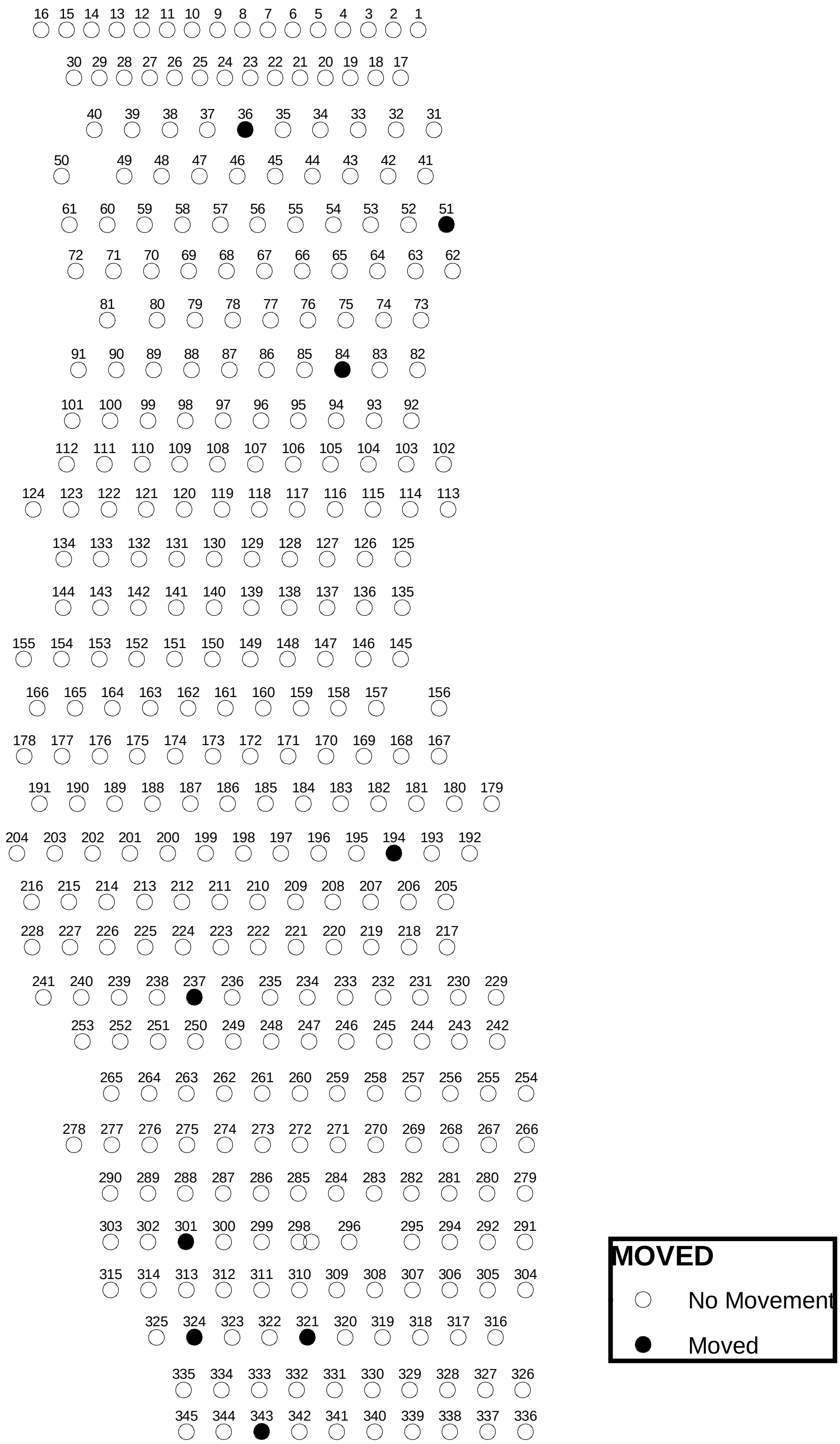


Molenaars River 2004
Stone Movement

Flood 2

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

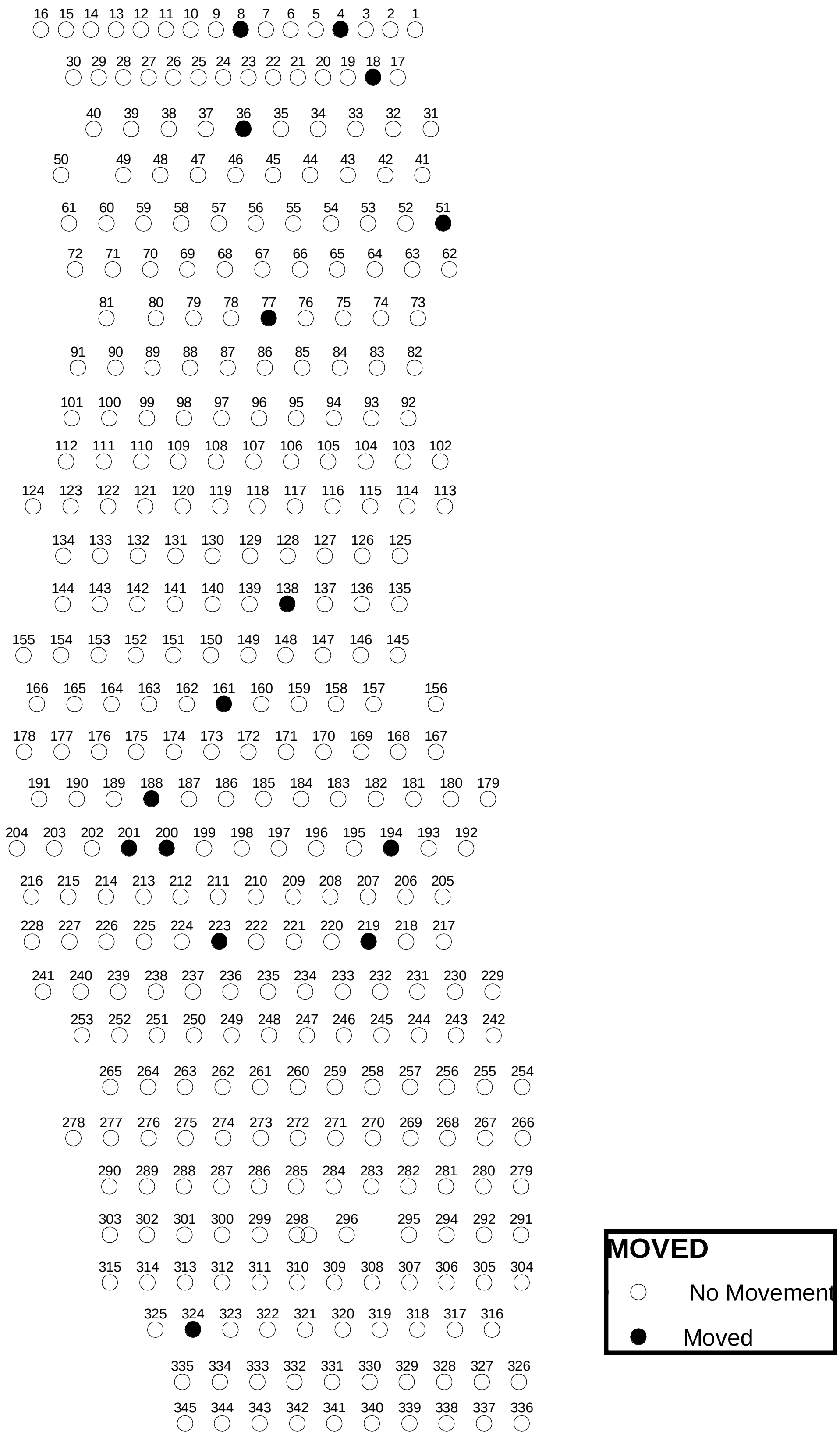


Molenaars River 2004
Stone Movement

Flood 3

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

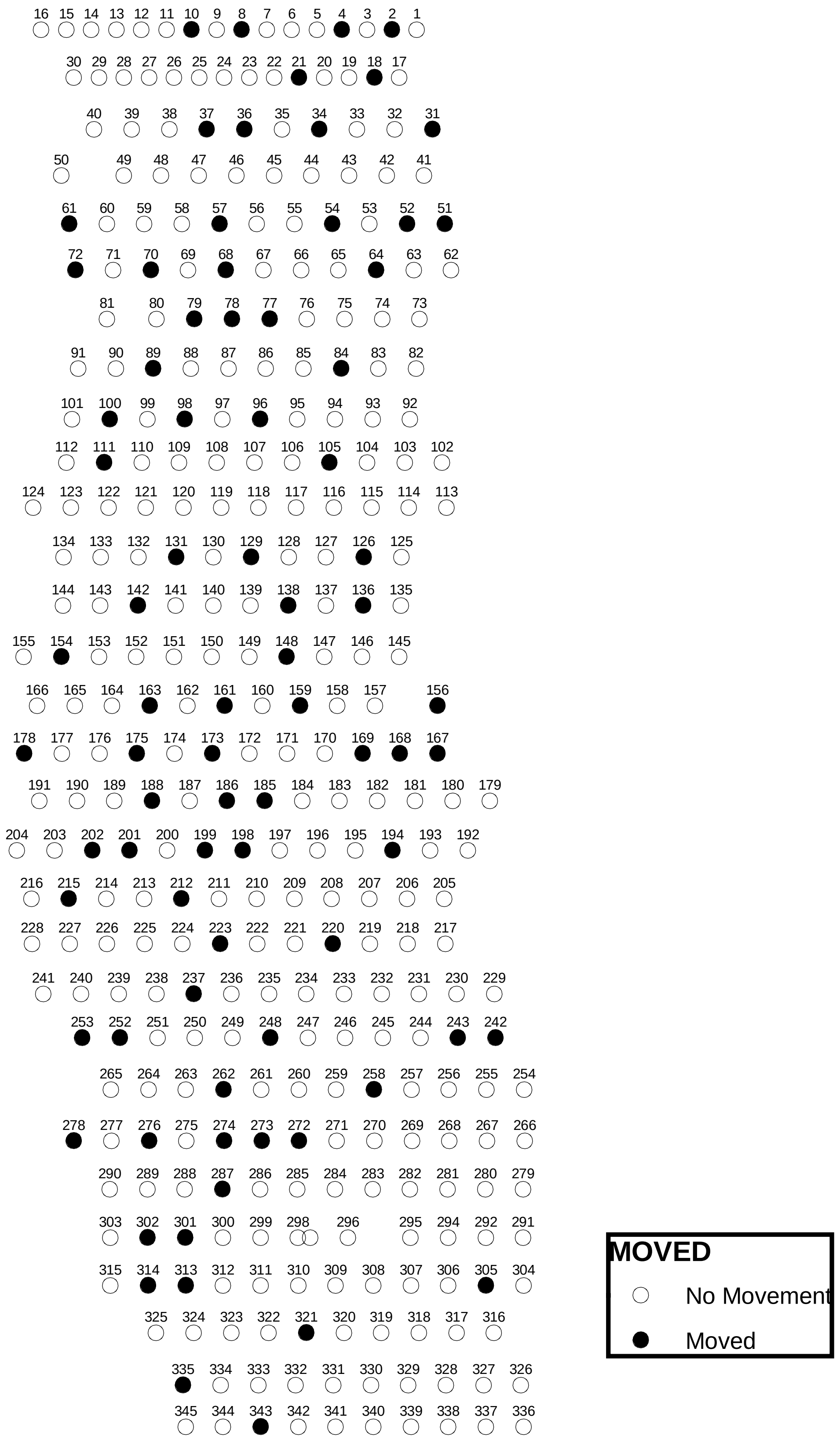


Molenaars River 2004
Stone Movement

Flood 4

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

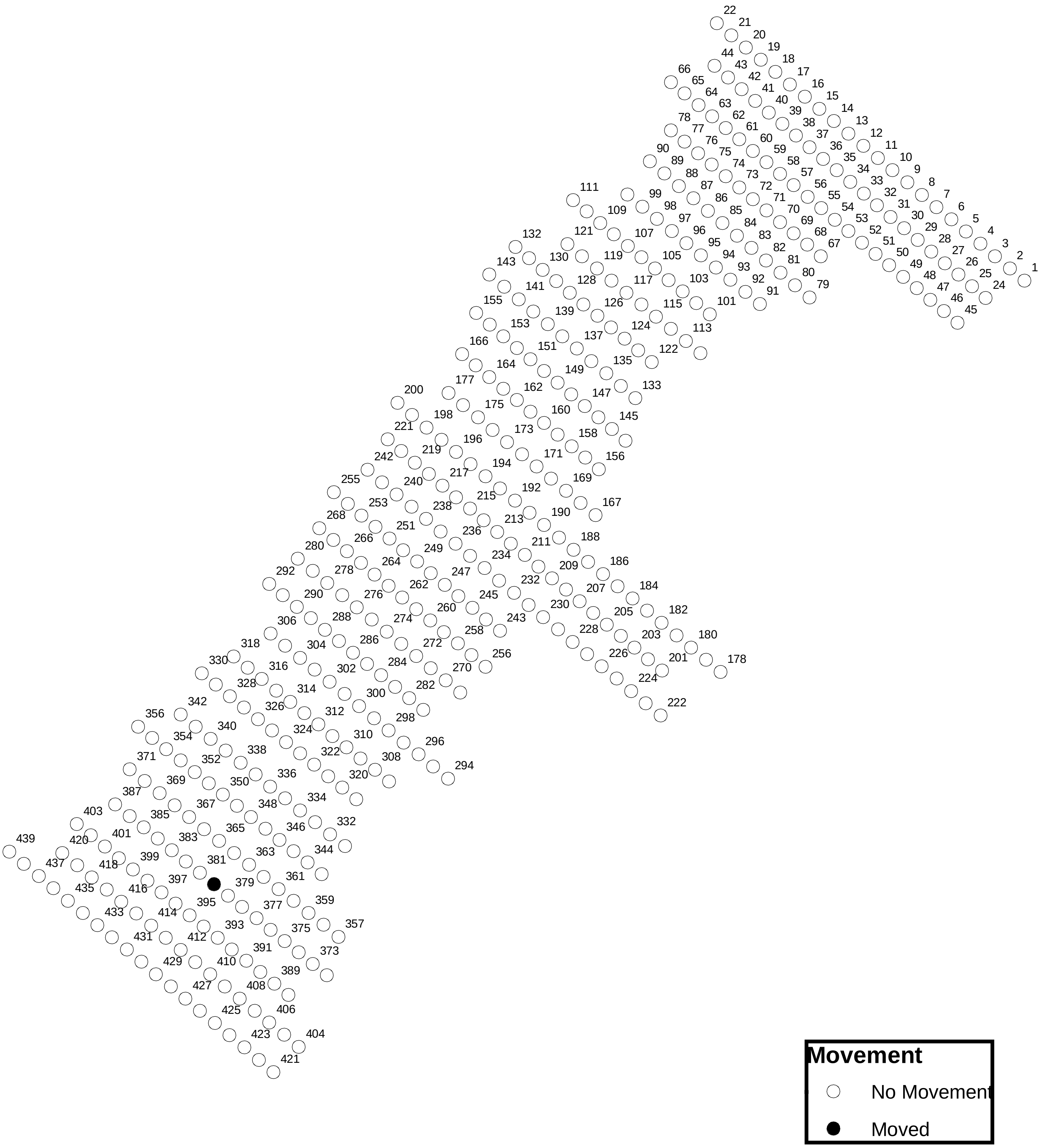


Molenaars River 2004
Stone Movement

Flood 5

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

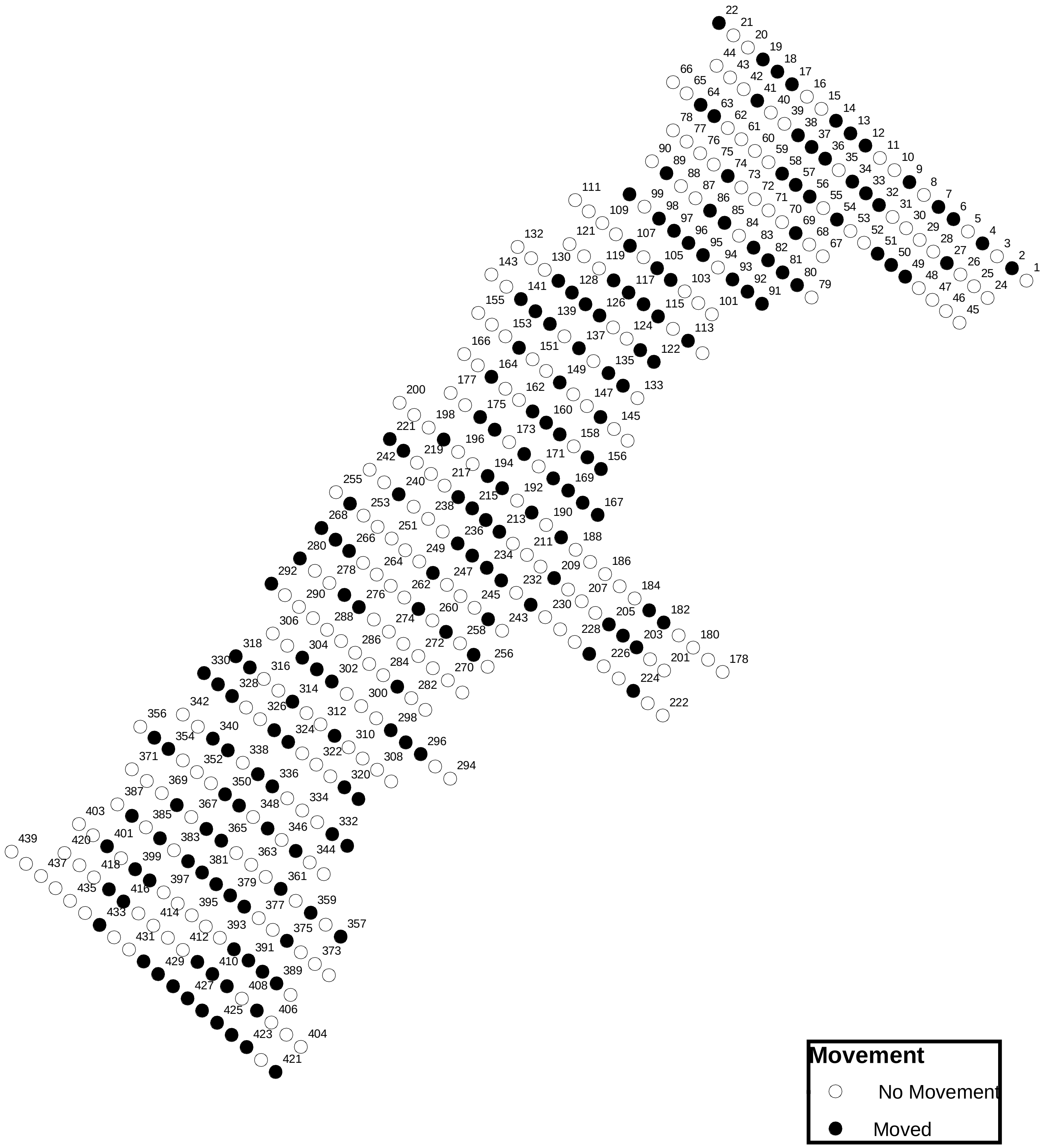


Berg River 2004
Stone Movement

Flood 1

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission

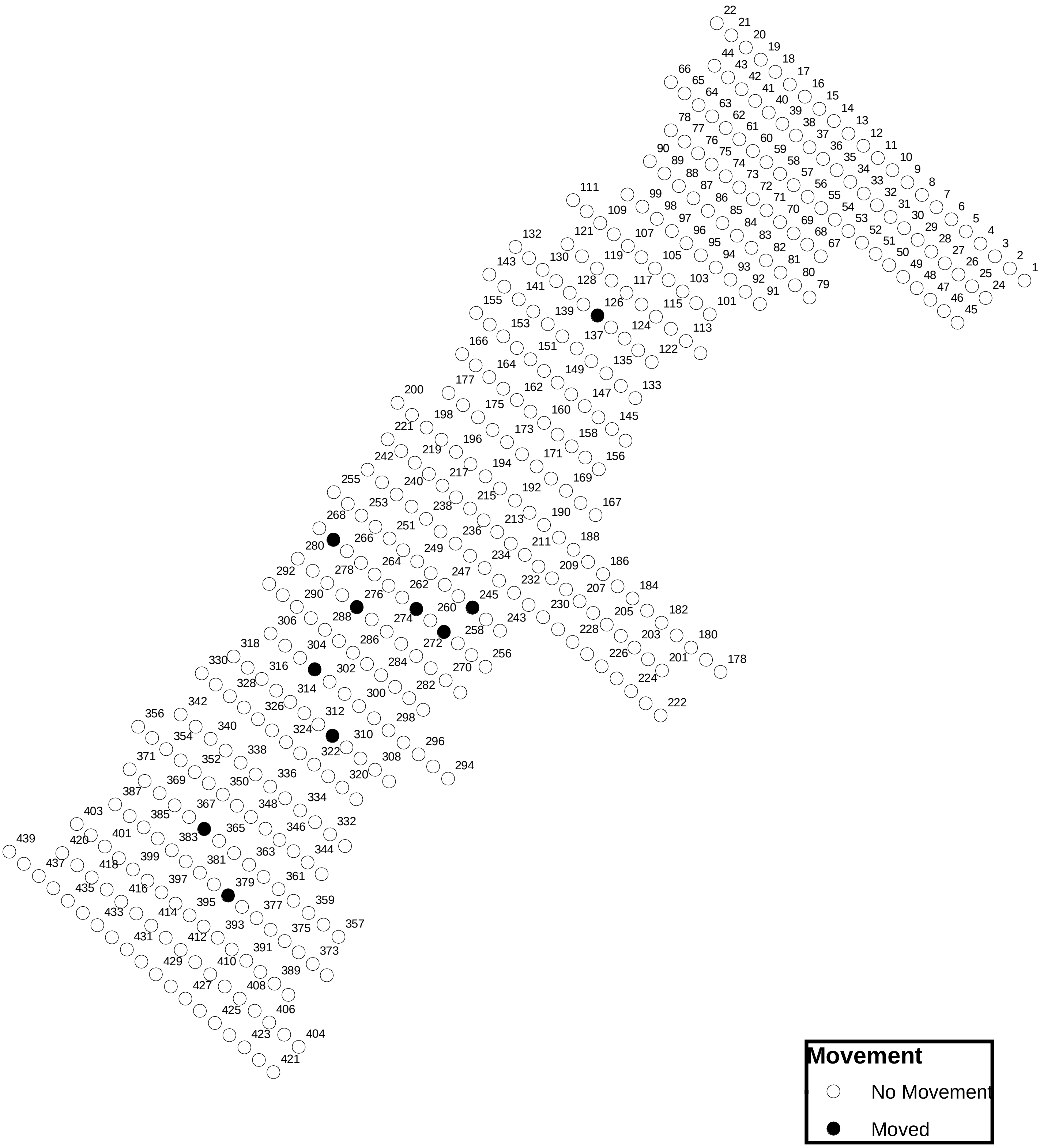


Berg River 2004
Stone Movement

Flood 2

WRC K5/1411
The Determination of Substrata Maintenance Flows in Cobble and Boulder Bed Rivers: Ecological and Hydraulic Considerations

Water Research Commission



Berg River 2004
Stone Movement

Flood 3

WRC K5/1411
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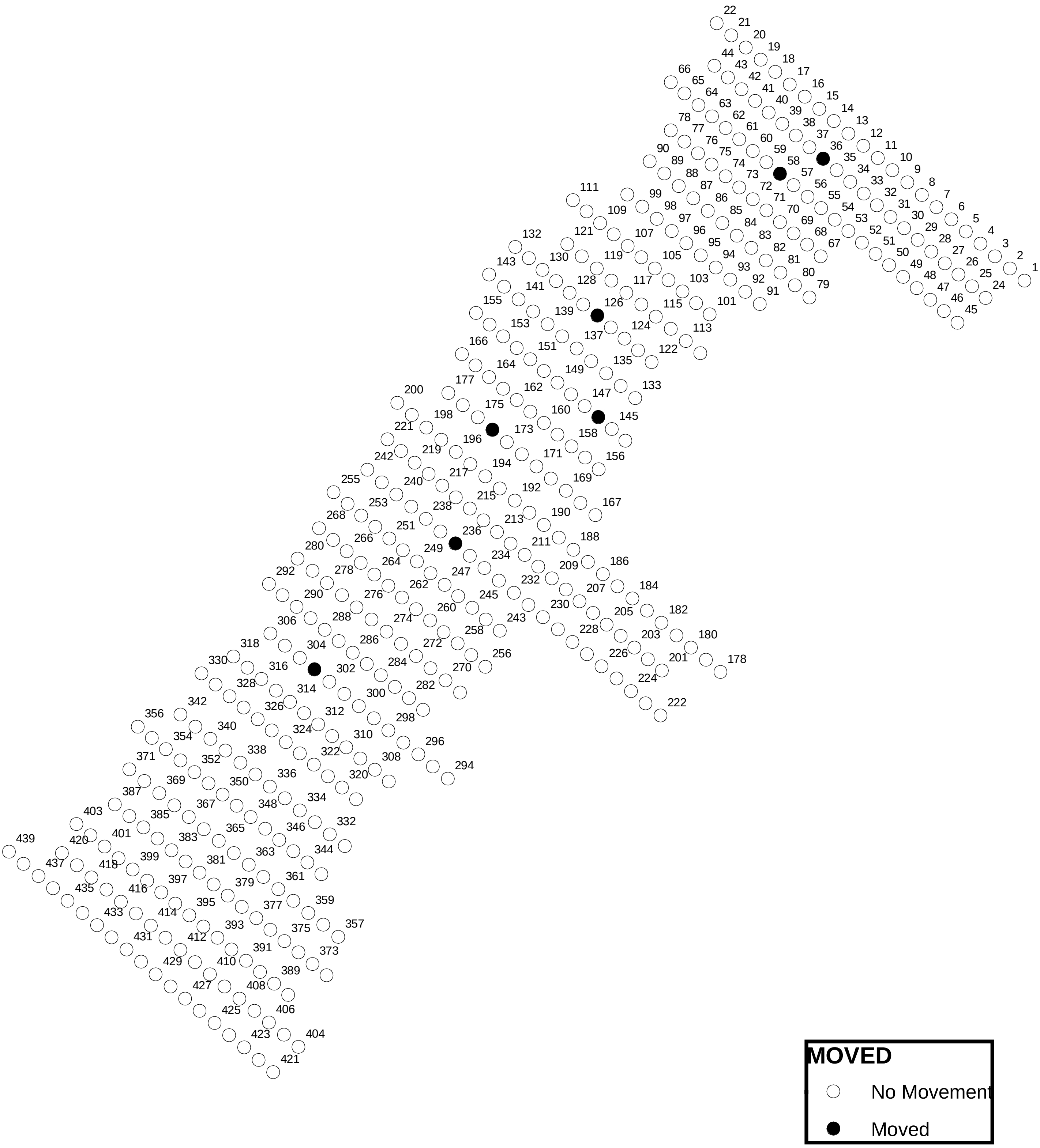

Berg River 2004
Stone Movement

Flood 4

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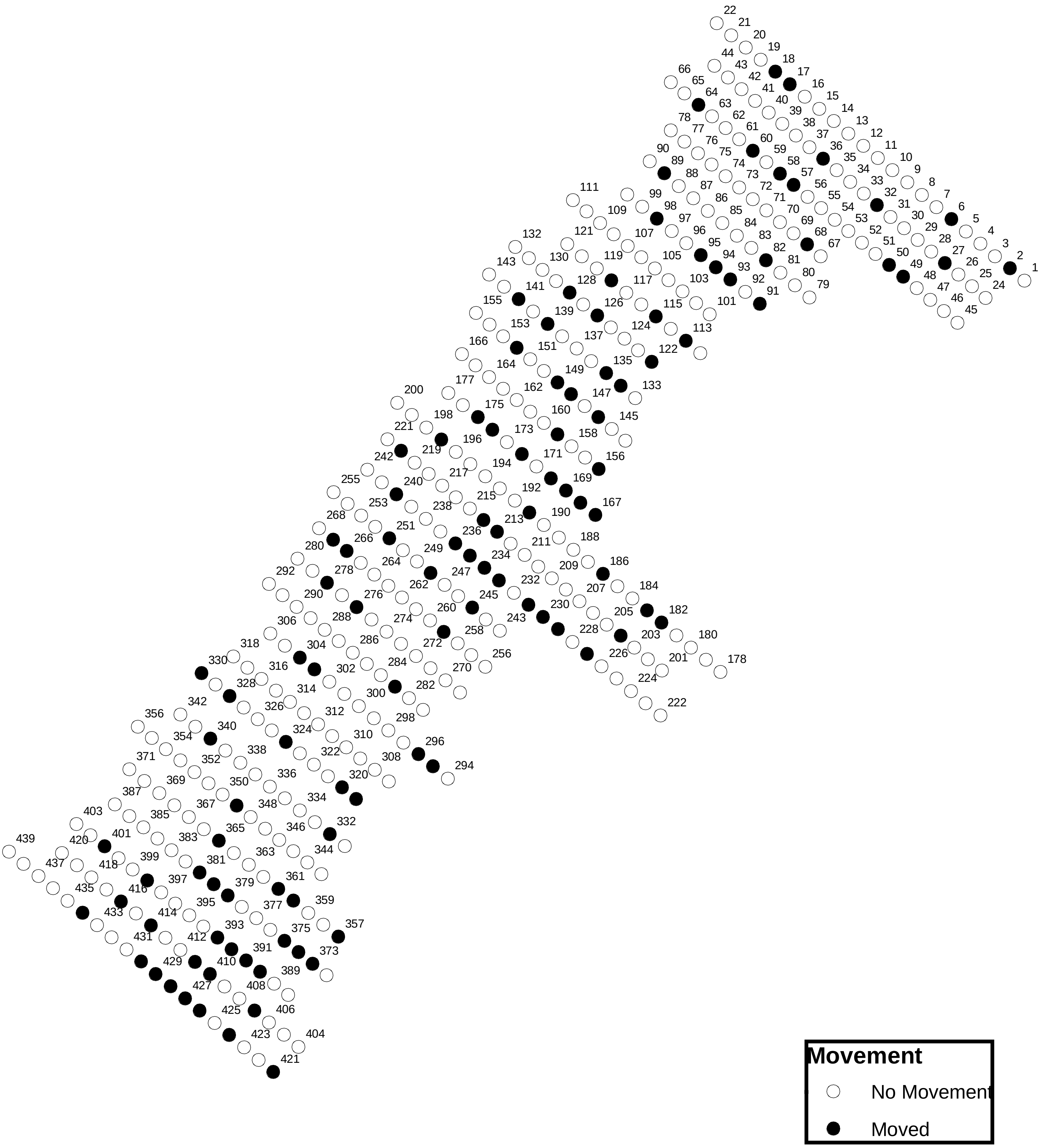

Berg River 2004
Stone Movement

Flood 5

WRC K5/1411
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